DESCRIPTION

SCREEN FOR PROJECTION DISPLAY AND OPTICAL SYSTEM FOR

PROJECTION DISPLAY SYSTEM

Technical Field

The present invention relates to a projection display screen and, more specifically, to a projection display screen which is easy to manufacture, is low in manufacturing cost, and has high-quality image display characteristics. The present invention also relates to a screen and an optical system for projection display system using a film with a function of converting light-outgoing direction.

Background Art

As a technology of the projection display screen in the related art, there exists a rear projection display screen including a diffusion film (for example, see Document 1, Okita et. al, Sumitomo Kagaku 1991-I, p. 37-48) for diffusing incident light from a specific angular range into a specific angular range (for example, see WO2004/034145).

This screen is different from a screen including a Fresnel lens, a lenticular lens, and a diffusion film used generally in the related art, and has very effective advantages such that the structure is simple and the cost can be reduced easily because it includes only the diffusion

film for diffusing the incident light from the specific

angular range into the specific angular range as shown in

Fig. 10, and that a diffuse light intensity distribution

characteristics are substantially uniform for the incident

light from the specific angular range as shown in Fig. 11

and hence variations in brightness in a screen is low.

On the other hand, in order to reduce the thickness of

an optical system for a rear projection display system, as

shown in Fig. 31 for example, it is necessary to arrange a

projector 20 not on a screen optical axis 10A, but at a

position shifted from the screen optical axis 10A to cause a

projector light to enter into a screen 10 from an oblique

direction. In general, most part of the projector light

entered into the screen 10 from the oblique direction does

not diffuse in the front direction of the screen where an

observer exists, but strongly in the direction of straight-

ahead transmission of the projector light. Therefore, in

order to achieve the thickness reduction, it is very

important to convert the out-going direction of the

projector light incoming into the screen from the oblique

direction into the front direction. ·

In order to achieve the conversion of direction of the

projector light as described above, as shown in Fig. 32 for

example, a technology to cause the projector light 20A

incoming from the oblique direction to pass through a prism

30 to convert the outgoing direction by the use of one or both of refraction 40 and total reflection 50 at an interface of the prism is known in the related art (for example, see Document 3, Shikama, S. et. al., SID'02Digest, p. 1250-1253)

Disclosure of Invention

Problems to be solved by the present invention

In the projection display screen, it is very important that the diffuse light intensity distribution characteristics can be arbitrarily controlled. A diffusing model by diffraction of the incident light is proposed as regards a principle of the diffusion film which plays an important role for realizing the characteristics in the above-described screen (see Document 1). However, the diffuse light intensity distribution characteristics cannot be described clearly by using the model, and hence the arbitrary control of the diffuse light intensity distribution characteristics is not realized.

In the case of the screen using the prism as described above (See Document 3), there are problems such that a stray light of the projector light may be generated at the complicated interface of the prism, which may lead to generation of a ghost on an image, and such that an external light is reflected (rearward reflection) to the incident

side (the side of the observer) at the interface, which may
results in lowering a contrast ratio. Furthermore, there
are problems such that corners of the prism are rounded
because of machining accuracy which may cause the projector
light to diffuse at the corners of the prism and hence the
efficiency of conversion of the outgoing direction is
lowered, thereby resulting in lowering of efficiency of
usage of the projector light, and such that there exists a
limit in angle of conversion of the outgoing direction
substantially because the efficiency of conversion of the
outgoing direction depends on the incident angle since the
projector light falls mainly on the corners of the prism in
the case of oblique incidence.

In this case, the efficiency of conversion of the
outgoing direction (or the efficiency of conversion of the
light-outgoing direction) represents a ratio in light-
strength between a light incoming into the light-outgoing
direction conversion film from a certain angle or angular
range and a light outgoing at a certain angle or angular
range, and the angles or angular ranges of incident light
and outgoing light are generally determined by the incident
angle of the projector light and the screen diffusion
characteristics. The angle of conversion of the outgoing
direction is an absolute value of a difference between the
direction of straight-ahead transmission and the outgoing

direction from the light-outgoing direction converting element.

Accordingly, the object of the present invention is to realize a diffusion film in which the arbitrary control of the diffuse light intensity distribution characteristics is possible, and the diffusing angular range is not varied with respect to an incident light from a specific angular range, and to provide a high-quality projection display system using the same as a screen. Furthermore, it is object of the present invention to realize a light-outgoing direction converting element that does not cause generation of ghost or lowering of contrast ratio of images resulting from the complex interface, is high in efficiency of conversion of the outgoing direction, and has no limit in the angle of conversion of the outgoing direction, and to provide a thin-model high-quality projection display using the same as a screen.

Means for Solving the Problems

After having devoted ourselves to study, in order to solve the above-described problems, the Inventors obtained a structure of a diffusion film in which superior characteristics such as:

1) arbitrary control of the diffuse light intensity distribution characteristics is possible;

2) angular range of diffusion does not vary with respect to the incident light from a specific angular range;

3) blur of the incident light is low;

4) high transmission coefficient and low back scattering are realized; and

5) polarization of the incident light is maintained;

can be realized by using a principle of optical waveguide to cause the direction of propagation of the incident light to be changed in flat plate waveguides laminated in layers in the direction in a plane.

Further, the inventors obtained a structure of a light-outgoing direction converting film in which superior characteristics such as:

6) ghost of an image due to a stray light is not generated;

7) the amount of rearward reflection is small;

8) efficiency of conversion of the light-outgoing direction is high;

9) there is no limit in the angle of conversion of the outgoing direction; and

10) polarization of an incident light is retained;

can be realized by changing the direction of propagation of incident light in a curved optical waveguide laminated in layers in the direction in the plane using a principle of the optical waveguide.

In other words, the present invention to be denoted by

Claims 1 to 16 is as follows.

The present Claim 1 is a projection display screen
having a diffusion film for diffusing light incoming from an
angular range of diffusion of an incident light into an
angular range of diffusion of an outgoing light, wherein the
diffusion film comprises a structure in which a plurality of
layers, each of which has a different refractive index from
the adjacent layers, constituting a plurality of optical
waveguides of a step index type forms a stripes arranged in
the banded state in a direction in a film plane and extend
in the direction of the layer inclination angle distributed
substantially in a top hat shape within a predetermined
angular range with respect to the direction of the film
thickness.

Claim 2 is a projection display screen having a
diffusion film for diffusing light incoming from an angular
range of diffusion of an incident light into an angular
range of diffusion of an outgoing light, wherein the
diffusion film comprises a structure in which a plurality of
layers, each of which has a different refractive index from
the adjacent layers, constituting a plurality of optical
waveguides of a step index type forms a stripes arranged in
a banded state in the direction in a film plane, one or more
peaks are included within a predetermined angular range with
respect to the direction of the film thickness, and the

plurality of layers extends in the direction of the layer inclination angle distributed substantially in a top hat shape excepting said peaks within the angular range.

Claim 3 is, in Claim 1 or 2, the structure of the diffusion film is a structure in which the relation between a film thickness L and a maximum value of the width of the strip y_{max} is: $L \geq 10 \times y_{max}$.

Claim 4 is a projection display screen having a diffusion film for diffusing light incoming from an angular range of diffusion of an incident light into an angular range of diffusion of outgoing light, wherein the diffusion film comprises a structure in which a plurality of layers constituting optical waveguides having a refractive index distribution that brings out a light-collecting property in the direction of the layer thickness extends in the direction of the film thickness or in the direction inclined from this direction with a layer length distributed within a predetermined range substantially in the top hat shape in a portion in the direction of the film thickness.

Claim 5 is, in Claim 4, the structure of the diffusion film has the refractive index distribution of the optical waveguides of a gradient index type, and a layer inclination angle θ, a maximum value L_{zmax} and a minimum value L_{zmin} of the layer length, and a pitch P of the optical waveguides satisfies the following expression: $L_{zmax} - L_{zmin} \geq (P/2) \times$

$\cos\theta$.

Claim 6 is a projection display screen having a diffusion film for diffusing light incoming from an angular range of diffusion of an incident light into an angular range of diffusion of an outgoing light, wherein the diffusion film comprises a structure in which a portion having the same structure as the diffusion film according to any one of Claims 1 to 3 and a portion having the same structure as the diffusion film according to Claim 4 or 5 are mixed in the direction of the film thickness or in the direction in the film plane.

Claim 7 is a projection display screen having a diffusion film for diffusing light incoming from an angular range of diffusion of an incident light into an angular range of diffusion of the outgoing light, wherein the diffusion film comprises a structure in which the structure of the diffusion film according to any one of the Claim 1 to 3 and the structure of the diffusion film according to Claim 4 or 5 are fused with each other.

Claim 8 is a screen using a film having a function of converting a light-outgoing direction comprising: a diffusion film for diffusing light incoming from an angular range of diffusion of the incident light into an angular range of diffusion of an outgoing light; and a light-outgoing direction converting film for causing light

incoming from an oblique direction to go out toward the front, wherein the light-outgoing direction converting film comprises a structure in which a plurality of layers, each of which has a different refractive index from the adjacent layers, forming a plurality of step index type optical waveguides is arranged in a banded state in the direction of a film plane, and extends so as to be bent with respect to the direction in the film thickness.

Claim 9 is a screen using a film having a function of converting a light-outgoing direction comprising: a diffusion film for diffusing light incoming from an angular range of diffusion of the incident light into an angular range of diffusion of an outgoing light; and a light-outgoing direction converting film for causing light incoming from an oblique direction to go out toward the front, wherein the light-outgoing direction converting film comprises a structure in which a plurality of layers forming optical waveguides having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness is arranged in a banded state in the direction in a film plane, and extends so as to be bent with respect to the direction of the film thickness.

Claim 10 is a screen using a film having a function of converting a light-outgoing direction comprising: a diffusion film for diffusing light incoming from an angular

range of diffusion of the incident light into an angular range of diffusion of an outgoing light; and a light-outgoing direction converting film for causing light incoming from an oblique direction to go out toward the front, wherein the light-outgoing direction converting film comprises a structure in which the structure according to Claim 8 and the structure according to Claim 9 are mixed in one or both of the film thickness direction and in the direction in the film plane.

Claim 11 is, in any one of Claims 8 to 10 the angular range of diffusion of the incident light of the diffusing film matches the outgoing angular range of the light-outgoing direction converting film.

Claim 12 is a screen having a light-outgoing direction converting/diffusing film that causes incident light from an oblique direction to diffuse and go out toward the front direction, wherein the light-outgoing direction converting/diffusing film comprises a structure in which a plurality of layers, each of which has different refractive index from the adjacent layers, forming a plurality of step index type optical waveguides is arranged in a banded state in the direction in a film plane, and extends so as to be bent with respect to the direction of the film thickness, and layer inclination angles are distributed substantially in a top hat shape.

Claim 13 is a screen having a light-outgoing direction converting/diffusing film that causes incident light from an oblique direction to diffuse and go out toward the front direction, wherein the light-outgoing direction converting/diffusing film comprises a structure in which a plurality of layers forming optical waveguides having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness is arranged in a banded state in the direction in a film plane, and extends so as to be bent with respect to the direction of the film thickness, and the length of the layers are distributed substantially in a top hat shape.

Claim 14 is a screen having a light-outgoing direction converting/diffusing film that causes incident light from an oblique direction to diffuse and go out toward the front direction, wherein the light-outgoing direction converting/diffusing film comprises a structure in which the structure according to Claim 12 and the structure according to Claim 13 are mixed in one or both of the film thickness direction and in the direction of the film plane, or a structure in which the structure according to Claim 12 and the structure according to Claim 13 are fused with each other.

Claim 15 is an optical system for projection display system comprising: a screen using a film having a function

of converting a light-outgoing direction according to any one of Claims 8 to 14, a projector which emits an incident light to the screen, wherein a projector aperture and arrangement of the projector matches an angular range of incidence of the screen.

Claim 16 is, in Claim 15, further including a reflection mirror which reflects the emitted light from the projector and causes the same to enter the screen, wherein the arrangement of the reflection mirror matches the angular range of incidence of the screen.

Effects of the present invention

According to the present invention, Claims 1 to 7, the projection display screen having superior characteristics such as:

1) arbitrary control of the diffuse light intensity distribution characteristics is possible;

2) angular range of diffusion does not vary with respect to the incident light from a specific angular range;

3) blur of incident light is low;

4) high transmission coefficient and low back scattering are realized; and

5) polarization of the incident light is maintained;

can be realized.

According to the present invention, Claims 8 to 14, a light-outgoing direction converting film and a light-

outgoing direction converting/diffusing film which can realize superior characteristics such as:

6) ghost of an image due to a stray light is not generated;

7) the amount of rearward reflection is small;

8) efficiency of conversion of the light-outgoing direction is high;

9) there is no limit in the angle of conversion of the outgoing direction; and

10) polarization of an incident light is retained;

and a high-quality thin-type projection display can be provided by using those films as a screen and matching the arrangement of the projector and the reflection mirror and the aperture of the projector and the aperture of the screen.

Brief Description of the Drawings

Fig. 1 is a pattern diagram showing an example of a film (1).

Fig. 2 is a pattern diagrams showing a layer inclination angle of the film (1).

Fig. 3 is a distribution chart showing a state in which the layer inclination angles of the film (1) are uniformly distributed within a predetermined range.

Fig. 4 is a distribution chart of the light intensity showing a relation between the incident angle and the outgoing angle of the film (1).

Fig. 5 is a pattern diagram showing an example of a film (2).

Fig. 6 is a cross-sectional view of a principal portion of Fig. 5 taken in the direction of film thickness and shown in an enlarged scale.

Fig. 7 is a drawing showing an example of refractive index distribution functions which brings out a light-collecting property in the direction of the layer thickness.

Fig. 8 is a distribution chart showing a state in which the layer length of the film (2) is distributed uniformly within a predetermined range.

Fig. 9 is a distribution chart of the light intensity showing a relation between the incident angle and the outgoing angle of the film (2).

Fig. 10 is a conceptual drawing of a rear projection display screen formed by a diffusion film for causing an incident light from a specific angular range to a specific angular range.

Fig. 11 is a distribution chart of the light intensity showing the diffusion characteristics of the screen shown in Fig. 10.

Fig. 12 is pattern diagrams; Fig. 12(a) shows an example of the film (3), (b) shows an example of the film (4), and (c) shows an example of the film (5).

Fig. 13 is a graph showing measurements of the

distribution of the layer inclination angle of an incident side portion of the diffusion film used in the present invention.

Fig. 14 is an explanatory drawing of derivation of a model expression of the film (1).

Fig. 15 is an explanatory drawing of derivation of the model expression of the film (1).

Fig. 16 is a drawing showing a refractive index distribution of an optical waveguide of the gradient index type.

Fig. 17 is a drawing showing light propagation within the optical waveguide of the gradient index type.

Fig. 18 is an explanatory drawing showing how to calculate the NA.

Fig. 19 is an explanatory drawing showing how to calculate the NA when an optical axis of the optical waveguide of the gradient index type is inclined by an angle θ with respect to a normal line of the film surface.

Fig. 20 is an explanatory drawing showing a structure and a diffusion characteristic of the diffusion film used in a first embodiment.

Fig. 21 is an explanatory drawing showing a structure and a diffusion characteristic of the diffusion film used in a second embodiment.

Fig. 22 is a pattern diagram of a cross-sectional side

view showing an example of a screen of the present invention, and an example of an optical system for rear projection display system using the same.

Fig. 23 is a pattern diagram showing an example of a light-outgoing direction converting film in a case in which a curved optical waveguide array is of a step index type.

Fig. 24 is an explanatory drawing of a coordinate of signs of angles and directions of rotation.

Fig. 25 is a pattern diagram showing an example of the light-outgoing direction converting film in a case in which the curved optical waveguide array is of a type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness.

Fig. 26 is a pattern diagram showing (a) an example in which the optical waveguide array of the step index type and the optical waveguide array of the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness are mixed in the direction of the film thickness, and (b) an example in which these arrays are mixed in the direction in a film plane.

Fig. 27 is an explanatory drawing showing relation between the angle range corresponding to an NA and the diameter of a lens, the focal length, the imaging magnification, and the imaging position.

Fig. 28 is an explanatory drawing showing a step index optical waveguide bent structure model.

Fig. 29 is an explanatory drawing showing a state in which the model in Fig. 7 is formed in the film.

Fig. 30 is an explanatory drawing showing a state in which the model in Fig. 7 is formed in the film.

Fig. 31 is an explanatory drawing showing reduction of the thickness of the optical system employing projection display system.

Fig. 32 is a conceptual drawing of a related art using a prism.

Fig. 33 is (a) a side view and (b) a plan view showing an example of a thin-type rear projection display system.

Fig. 34 is an explanatory drawing of a definition of a linear gradient index optical waveguide.

Fig. 35 is an explanatory drawing showing derivation of an angle which determines the NA in the linear gradient index optical waveguide.

Fig. 36 is an explanatory drawing showing a polygonal approximation model of a bent waveguide of a gradient index type.

Fig. 37 is an explanatory drawing showing a state in which the model in Fig. 36 is formed in the film.

Fig. 38 is an explanatory drawing of an analysis of an angle of an optical axis that makes the NA symmetry on the

upper side and the lower side on the outgoing side of the bent waveguide of the gradient index type.

Fig. 39 is an explanatory drawing of a radius of curvature of a polygonal approximation model of the bent waveguide of the gradient index type.

Fig. 40 is an explanatory drawing showing a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness other than the parabola type.

Fig. 41 is an explanatory drawing showing (a) a general outline of the optical film used in a third embodiment and (b) a summary of experiment for converting an outgoing direction using the bent waveguide manufactured from the optical film.

Fig. 42 is an explanatory drawing showing a method of calculating the thickness of the film.

Reference Numerals

    1   layer (curved optical waveguide = bent waveguide)

    1_A layer (core)

    1_B layer (clad)

    1_C layer (layer having the distribution of refractive indexes that brings out the light-collecting property in the direction of the layer thickness)

    2   light-outgoing direction converting film

2_X remaining portion (film portion other than optical waveguide)

3   diffusing film

4, 4_1, 4_2, 4_3, 4_4, 4_L linear gradient index optical waveguide

5, 6, 7, 8, 15, 16, 17, 18   light beam

9   optical film

9_1, 9_2 layer

9A   optical film strip

10   screen

10A   screen optical axis

11   light source

11_1 incident light

11_2 outgoing light

12   transparent medium

20   projector (optical engine)

20A   projector light

21   object (image display panel)

30   prism

40   refraction

50   total reflection

51   film(1)

51_1 layer (core)

51_2 layer (clad)

52   film(2)

52_1 layer

53   film(3)

54   film(4)

53_1, 54_1 portion having the same structure as film (1)

53_2, 54_2 portion having the same structure as film (2)

55   film(5)

55_A structure formed by fusing the structure of film(1) and the structure of the film (2)

60   diffusion film (scattering film)

61   protective plate

62   projector

M1, M3   mirror

M2   non-spherical mirror

Best Mode for Carrying Out the Invention

In the present invention, an angle describing the optical system is, as shown in Fig. 24, such that an angle of a reference direction (for example, a horizontal direction (z-direction)) is 0°, and an angle rotated leftward from the reference direction (counterclockwise) is represented as positive (+), and the angle rotated rightward (clockwise) is represented as negative (-).

About Claims 1 to 7

Firstly, a diffusion film (film(1)) according to Claims 1 to 3 will be described.

Fig. 1 is a pattern diagram showing an example of a film (1). A film (1) 51 can cause light incoming from an angular range of diffusion of the incident light θ_{in} to be diffused in an angular range of diffusion of the outgoing light θ_{out}. A z-axis extends in the direction parallel to the direction of thickness L of the film (1) 51, and an x-axis and a y-axis orthogonal to each other in a plane perpendicular to the z-axis.

The film (1) 51 has a structure in which layers 51_1, 51_2 having different refractive indexes n_1, n_2 ($n_1 > n_2$) from the adjacent layers form a stripe pattern (widths of the stripes y_1, y_2) arranged in one direction in a film plane (xy-plane) alternately, and extend in a direction of an averaged inclination angle θ with respect to the direction of the film thickness (z-direction). The conditions of the widths of the stripes y_1, y_2 of the layers 51_1, 51_2 for causing the incident light to be diffused uniformly are represented as follows using the thickness L of the film (1) 51.

$$L \geq 10 \times y_1, \qquad L \geq 10 \times y_2$$

A layer inclination angle θ_L is defined by an inclination angle of the interface of the layer with respect to the z-axis, and varies within a range from a minimum inclination angle $(\theta - \Delta\theta_{max})$ to a maximum inclination angle $(\theta + \Delta\theta_{max})$ depending on the position in the direction of the thickness of the film (1) 51 as shown in Fig. 2. Here, θ

represents the average inclination angle, $\Delta\theta_{max}$ corresponds to 1/2 of the range of fluctuations of θ_L.

Here, the conditions of the average inclination angle θ for causing the light loss to be eliminated are represented as follows using the refractive index n_1.

$-\sin^{-1}(1/n_1) \leq \theta \leq \sin^{-1}(1/n_1)$

The respective layers in the film (1) 51 having the above-described structure are the same as in the optical waveguides of a step index type. In these layers, the conditions of distribution of the layer inclination angle for causing the incident light to be diffused uniformly is such that the distribution of the existentive probability of the layer inclination angle θ_L becomes the top hat shape (rectangular wave) when the layer inclination angle θ_L is within a predetermined range ($(\theta - \Delta\theta_{max})$ to $(\theta + \Delta\theta_{max})$) as shown in Fig.3. Since it is difficult to achieve a complete top hat shape in reality, in the present invention, the existential probability of the layer inclination angle in a predetermined range is defined to be distributed in substantially top hat shape while allowing the fluctuations in the existential probability of the plateau section of the distribution curve within the range of ±40% of the average value and fluctuations in the respective domain widths at a riding edge and a falling edge at a riding edge and a falling edge within the range of ±30% of the most-likelihood

half width of the entire distribution curve.

Also, there may be a case in which one or more peaks
are mixed within the substantially top hat shaped
distribution of the layer inclination angle within a
predetermined range in reality. However, since the
advantages of the present invention is not affected
adversely if the peak value of the existential probability
does not exceed 1000% of the average value with the peaks
excluded, such a case is also included in the present
invention. Preferably, the number of peaks is on the order
of five or less.

The uniformity of the diffuse light intensity depends
not only on the existential probability of the layer
inclination angle, but also on the length of the layer, and
as the repetition of multiple reflections of the incident
light increases with increase in length of the layer, more
uniform diffuse light intensity distribution characteristics
is obtained. Therefore, a permissible range becomes wider
than that described above in the case of a thick film having
the film thickness L larger than $50 \times y_{max}$. Here, y_{max} means
either one of y_1 and y_2 which is greater.

With the film (1) which satisfies the conditions
described above, the light incoming thereto from the angular
range of diffusion of the incident light is diffused into
the angular range of diffusion of the outgoing light at

substantially uniform light intensity.

Here, the angular range of diffusion of the incident light θ_{in} are represented by the following expression.

$Min[\theta_1', \theta_1'', \theta_2', \theta_2''] \leq \theta_{in} \leq Max[\theta_1', \theta_1'', \theta_2', \theta_2'']$

$\theta_1' = \sin^{-1}[n_1 \times \sin\{\theta + \Delta\theta_{max} + \cos^{-1}(n_2/n_1)\}]$ ....(1)

$\theta_1'' = \sin^{-1}[n_1 \times \sin\{\theta - \Delta\theta_{max} + \cos^{-1}(n_2/n_1)\}]$ ....(2)

$\theta_2' = -\sin^{-1}[n_1 \times \sin\{-(\theta + \Delta\theta_{max}) + \cos^{-1}(n_2/n_1)\}]$ ....(3)

$\theta_2'' = -\sin^{-1}[n_1 \times \sin\{-(\theta - \Delta\theta_{max}) + \cos^{-1}(n_2/n_1)\}]$ ....(4)

$Max\{a, b\}$ represents either one of a and b which is greater, and $Min\{a, b\}$ represents either one of a and b which is smaller (hereinafter).

The angular range of diffusion of the outgoing light θ_{out} is represented as follows.

$Min[\theta_1', \theta_1'', \theta_2', \theta_2''] \leq \theta_{out} \leq Max[\theta_1', \theta_1'', \theta_2', \theta_2'']$ ....(5)

The above-described relation between the incident angle and the outgoing angle is shown in Fig. 4.

The above-described angles $\theta_1', \theta_1'', \theta_2', \theta_2''$ are derived as follows.

The film (1) has an optical waveguides of the step index type (hereinafter, referred to also as waveguides simply) being arranged in one-dimensional array and constitutes a layer structure, and the direction of the layers are fluctuated. Assuming that the average direction of the layers is θ, and a model having fluctuations of $\pm\Delta\theta_{max}$

with respect to θ will be considered. When this model has a
uniform fluctuation in distribution of the layer inclination
angle between $(\theta - \Delta\theta_{max})$ and $(\theta + \Delta\theta_{max})$, a light beam having
an angle between a critical angle determined by $(\theta - \Delta\theta_{max})$
and a critical angle determined by $(\theta + \Delta\theta_{max})$ repeats
multiple reflections, and the angle therebetween are
uniformly filled. In this mechanism, when the reflecting
surface is not constituted by straight films but curves, and
a plane wave (light beam) incoming from a certain direction
is converted into a curved wave (spherical wave when the
reflecting surface is formed of curves of second order), and
when the angle exceeds the critical angle, there is little
reflection occurs any longer and diffusion characteristics
of the top hat type which does not depend on the direction
of incidence, appear. The angle which determines the top
hat characteristics is the critical angle determined by $(\theta -$
$\Delta\theta_{max})$ and the critical angle determined by $(\theta + \Delta\theta_{max})$.

There are two critical angles determined by the layer
inclination angle $(\theta - \Delta\theta_{max})$ on the upper side and the lower
side of the waveguide, and likewise, there are two critical
angles determined by the layer inclination angle $(\theta + \Delta\theta_{max})$
on the upper side and the lower side of the waveguide, and
hence there exist four angles in total.

Derivation in the case of the layer inclination angle $(\theta$
$+ \Delta\theta_{max})$ will be shown first. Assuming that n_{air} represents a

refractive index of air, n_1 represents a reflective index of core 51_1, n_2 represents a refractive index of clad 51_2 ($n_1 > n_2$), when Snell's Law is applied to the interface of the film on the incident side in Fig. 14,

$$n_{air} \times \sin\theta_1' = n_1 \times \sin\theta_3 \qquad ....(A1)$$

is obtained.

Then, the limit angle, that is, the critical angle at which the light entered into the core 51_1 totally reflects on the upper interface with respect to the clad 51_2 is given by the following expression.

$$n_1 \times \sin\{\pi/2 - \theta_3 + (\theta + \Delta\theta_{max})\} = n_2 \times \sin 90° \qquad ....(A2)$$

From the expressions (A1) and (A2),

$$\theta_1' = \sin^{-1}[n_1 \times \sin\{\theta + \Delta\theta_{max} + \cos^{-1}(n_2/n_1)\}] \qquad ....(A3)$$

is obtained.

Subsequently, the angle which is determined by the lower interface of the waveguide will be derived. When Snell's Law is applied to the film interface of the incident side in Fig. 15,

$$n_{air} \times \sin(-\theta_2') = n_1 \times \sin(-\theta_4) \qquad ....(A4)$$

is obtained.

Then, the limit angle (critical angle) at which the light entered into the core 51_1 totally reflects on the lower interface with respect to the clad 51_2 is given by the following expression.

$$n_1 \times \sin\{\pi/2 - (-\theta_4) - (\theta + \Delta\theta_{max})\} = n_2 \times \sin 90° \qquad ....(A5)$$

From the expressions (A4), (A5),

$$\theta_2' = -\sin^{-1}[n_1 \times \sin\{-(\theta + \Delta\theta_{max}) + \cos^{-1}(n_2/n_1)\}] \quad \dots \dots \text{(A6)}$$

is obtained.

A method of derivation of the angles θ_1' and θ_2' which are determined by the upper and lower core/clad interfaces in the case of the layer inclination angle $(\theta + \Delta\theta_{max})$ are described above.

Likewise, in the case of the layer inclination angle $(\theta - \Delta\theta_{max})$, the angles can be obtained by substituting $(\theta - \Delta\theta_{max})$ for $(\theta + \Delta\theta_{max})$ in the expressions (A3) and (A6), and the expressions are as follows.

$$\theta_1'' = \sin^{-1}[n_1 \times \sin\{\theta - \Delta\theta_{max} + \cos^{-1}(n_2/n_1)\}] \quad \dots \dots \text{(A7)}$$

$$\theta_2'' = -\sin^{-1}[n_1 \times \sin\{-(\theta - \Delta\theta_{max}) + \cos^{-1}(n_2/n_1)\}] \quad \dots \dots \text{(A8)}$$

Derivation of the four angles is now completed.

In the case of the film (1), the diffuse light intensity distribution characteristics of the outgoing light are determined by the existential probability of the layer inclination angle. In the example shown above, since the incident light is diffused in the light intensity distribution of the top hat type, the existential probability of the layer inclination angle is distributed in the top hat shape as shown in Fig. 3. However, by varying the existential probability so as to be distributed in substantially top hat shape (including the trapezoidal shape or the like) from the theory based on the same physical law,

other desired diffuse light intensity distribution characteristics other than that of the top hat type (such as trapezoidal shape, Gaussian distribution or the like) may be obtained.

In the example shown in Figs. 1 to 2, the film in which the layer inclination angle is fluctuated only in the direction of the thickness and the layer inclination angle is not fluctuated in the direction in the plane has been described. However, by causing the layer inclination angle to be fluctuated not only in the direction of thickness, but also in the direction in the plane, or by causing the layer inclination angle to be fluctuated only in the direction in the plane, and varying the existential probability of the layer inclination angle according to the theory based on the same physical law as the example shown above, desired diffuse light intensity distribution characteristics can be achieved.

Although the film surface is a planer surface in the example shown in Fig. 1 to Fig. 2, a case in which the film surface is a curved surface can be treated in the same manner by considering the curved surface to be a group of minute planes.

Although there are two types of layers in the example in Fig. 1 to Fig. 2, a structure having three or more types of layers may also be treated in the same manner.

Subsequently, the diffusion film (film (2)) stated in Claims 4 to 5 will be described.

Fig. 5 is a pattern diagram showing an example of a film (2). A principal portion of Fig. 5 is shown in an enlarged scale in Fig. 6. A film (2) 52 has a structure as shown below and hence the light incoming from the angular range of diffusion of the incident angle θ_{in} can be diffused into the angular range of diffusion of the outgoing light θ_{out}. The z-axis extends in the direction parallel to the direction of thickness L of the film (2) 52, and the x-axis and y-axis orthogonal to each other in the plane perpendicular to the z-axis.

The film (2) 52 has a structure in which a plurality of layers 52_1 of a thickness b_1 which is partitioned by interfaces at an inclination angle θ with respect to the z-direction (θ which is the same sign as the average inclination angle in film (1) is used) are laminated in a y-direction at a portion in the direction of the film thickness. The layer 52_1 constitutes an optical waveguide having a refractive index distribution which brings out a light-collecting property in the direction of the layer thickness. The portion of the film (2) other than the layer 52_1 has a constant refractive index n_g. The conditions of the thickness b_1 of the layer for causing the incident light to be diffused uniformly are represented as follows using

the thickness L of the film (2); $L \geq 10 \times b_1$.

The angle between the interfaces of the layer 52_1 (angle of the layer) θ with respect to the z-direction may be 0° (the extending direction of the layer 52_1 is perpendicular to the film plane). The layer length of the layer 52_1 (the length in the direction of the film thickness) is assumed to be L_{zmin} to L_{zmax}. As shown in Fig. 6, axes obtained by rotating the z-axis and the y-axis about the x-axis by the angle θ are represented by an a-axis and a b-axis. In other words, the b-axis extends in parallel with the direction of the layer thickness, and the a-axis extends perpendicularly with respect to the b-axis and the x-axis.

There is an example of the refractive index distribution function which brings out the light-collecting property in the direction of the layer thickness as shown in Fig. 7. Fig. 7(a) shows a waveguide of a gradient index type which has a refractive index distribution represented by the following expression.

$$n(b) = n_1 \times (1 - (A/2) \times b^2)), \quad -b_1/2 \leq b \leq b_1/2,$$

A: coefficient   ....(6)

Here, the conditions of the layer length for causing the incident light to be diffused uniformly are represented by the following expressions using the layer inclination angle θ, the maximum value L_{zmax} and the minimum value L_{zmin} of the layer length, and the pitch P of the optical waveguide.

$$L_{zmax} - L_{zmin} \geq (P/2) \times \cos\theta \qquad ....(7)$$

$$P = 2 \times \pi/\sqrt{A} \qquad ....(8)$$

$$A = (8/b_1^2) \times (n_1 - n_2)/n_1 \qquad ....(9)$$

At this time, it is ideal that the existential probability of the layer length is distributed in the top hat shape as shown in Fig. 8. However, since it is difficult to achieve the complete top hat shape in reality, in the present invention, the existential probability of the layer length in the range between L_{zmin} and L_{zmax} is defined to be distributed in substantially top hat shape while allowing the fluctuations in the existential probability of the plateau section of the distribution curve within the range of ±40% of the average value and fluctuations in the domain width at the riding edge and the falling edge within the range of ±30% of the most-likelihood half width of the entire distribution curve.

With the film (2) which satisfies the conditions described above, the light incoming thereto from the angular range of diffusion of the incident light is diffused into the angular range of diffusion of the outgoing light at a substantially uniform light intensity.

Here, the angular range of diffusion of the incident light θ_{in} is represented by the following expressions.

$$\theta_{NA2} \leq \theta_{in} \leq \theta_{NA1} \qquad ....(10)$$

$$\theta_{NA1} = \sin^{-1}\{n_g \times \sin(\theta + \theta_{g1})\} \qquad ....(11)$$

$\theta_{NA2} = \sin^{-1}\{n_g \times \sin(\theta - \theta_{g1})\}$ .... (12)

$\sin\theta_{g1} = (n_1/n_g) \times \sin\{\tan^{-1}(n_1 \times \sqrt{A} \times b_1/2)\}$ .... (13)

The angular range of diffusion of the outgoing light θ_{out} is represented as follows.

$\theta_{NA2} \leq \theta_{out} \leq \theta_{NA1}$ .... (14)

The above-described relation between the incident angle and the outgoing angle are shown in Fig. 9.

Since the light entered into an optical waveguide of the gradient index type having the refractive index distribution in Fig. 7(a) propagates within the waveguide while changing the direction of travel in the range of:

$\theta - \tan^{-1}(n_1 \times \sqrt{A} \times b_1/2) \sim \theta + \tan^{-1}(n_1 \times \sqrt{A} \times b_1/2)$ .... (15)

the diffuse light intensity distribution characteristics are determined by the difference in the existential probability of the layer length.

As described above, in one mode of the film (2), since the optical waveguides of the gradient index type have an array structure, and the direction of light propagation differs by the position in the direction of the length of the optical waveguide, the outgoing angle at the outgoing end surface differs from waveguide to waveguide when there are fluctuations in length of the waveguides, which brings out the diffusion of light. Therefore, when variation in the direction of propagation in the waveguide is linear with

respect to the length of the waveguide, the diffusion characteristics of the top hat type is realized because of the uniform fluctuation in length.

Expressions for analyzing this mechanism will now be derived and described.

First of all, attention is focused on one of the optical waveguides. As shown in Fig. 16, it is assumed that the refractive index distribution function is given by the following quadratic function;

$$n(r) = n_1 \times (1 - A/2 \times r^2) \qquad ....(B1)$$

symmetrically from the center of the optical waveguide.

Here, n_1 represents a refractive index on the center axis, A represents a distribution constant of the refractive index, and r represents a distance from the center. Assuming that a refractive index at position coordinates $\pm b_1/2$ on both interfaces in the direction of the thickness of the optical waveguide is n_2, the expression:

$$A = (8/b_1^2) \times (n_1 - n_2)/n_1$$

As shown in Fig. 17, a z-axis is placed at the center of the optical waveguide of the gradient index type, and the position of the light incident surface is assumed to be z = z_1. The distance from the z-axis is r. The distance from the z-axis at the position of the light incident surface is represented by r_1, the direction of the light beam in the optical waveguide at this position is assumed to be $r_1^* =$

$dr_1/dz = \tan\theta_1$. Likewise, the position of the light outgoing surface is assumed to be $z = z_2$, and the distance from the z-axis is represented by r_2, and the direction of the light beam in the optical waveguide at this position is assumed to be $r_2{}^* = dr_2/dz = \tan\theta_2$.

Between the vector that represents the position and the direction of the light beam on the light incident surface (input vector) $[r_1, r_1{}^*]$ and the vector that represents the position and the direction of the light beam on the light outgoing surface (output vector) $[r_2, r_2{}^*]$, a relation as represented by the following expression (B2) is established.

[Expression 1]

$$\begin{bmatrix} r_2 \\ r_2^* \end{bmatrix} = \begin{bmatrix} \cos\left\{\sqrt{A}(z_2 - z_1)\right\} & \dfrac{\sin\left\{\sqrt{A}(z_2 - z_1)\right\}}{n_1\sqrt{A}} \\ -n_1\sqrt{A}\sin\left\{\sqrt{A}(z_2 - z_1)\right\} & \cos\left\{\sqrt{A}(z_2 - z_1)\right\} \end{bmatrix}\begin{bmatrix} r_1 \\ r_1^* \end{bmatrix} \quad \ldots(B2)$$

The expression (B2) means that being irrespective of the incident position r_1 of the light and the direction $r_1{}^*$ of the light beam at this position, distance from the z-axis and direction of the light beam at a position is periodically restored to the initial state when traveled by a certain distance toward the z-axis. The distance in the direction of the z-axis which is restored periodically to the original state is a pitch (P) of the optical waveguide of the gradient index type. For the sake of simplicity, when the position of the incident surface is assumed to be

$z_1 = 0$, the expression (B3) is obtained from the expression (B2).

[Expression 2]

$$\begin{bmatrix} r_2 \\ r_2^* \end{bmatrix} = \begin{bmatrix} \cos\left(\sqrt{A}z_2\right) & \dfrac{\sin\left(\sqrt{A}z_2\right)}{n_1\sqrt{A}} \\ -n_1\sqrt{A}\sin\left(\sqrt{A}z_2\right) & \cos\left(\sqrt{A}z_2\right) \end{bmatrix} \begin{bmatrix} r_1 \\ r_1^* \end{bmatrix} \qquad \ldots(B3)$$

The pitch (P) is obtained from the expression (B3). Since the components of 2 rows × 2 columns in the expression (B3) are functions of sin and cos, when the $\sqrt{A}$ × z_2 is changed by 2π, the position and the direction of the light beam is restored to the initial state, and hence the pitch (P) can be obtained from the following expression.

$\sqrt{A}$ × P = 2π .... (B4)

Therefore;

P = $2\pi/\sqrt{A}$ .... (B5)

Subsequently, the numerical aperture NA is calculated. The NA is given by the largest angle out of the angles between the light beam which can be propagated in the optical waveguide of the gradient index type and the optical axis. In order to obtain the value of NA, as shown in Fig. 18, the length z_2 of the optical waveguide of the gradient index type is represented by P/4, and the position of the incident light beam on the plane of $z_1 = 0$ is assumed to be $r_1 = b_1/2$ (an end of the optical waveguide in the direction of thickness) and the direction of the light beam is assumed

to be parallel with the optical axis $(r_1* = dr_1/dz = \tan\theta_1 = 0)$.

Therefore, the input vector $[r_1 \ r_1*]$ will be expressed by the following expression (B6). While the output vector $[r_2 \ r_2*]$ will be expressed by the following expression (B7), since $r_2 = 0$ as the length of the optical waveguide of the gradient index type $z_2=P/4$, and the incident light beam is parallel to the optical axis. By using the expression (B5) : $P = 2\pi/\sqrt{A}$, the expression : $z_2 = P/4$ becomes the following expression (B8). Then substitution of the expressions (B6), (B7) and (B8) into the expression (B3), and arrangement thereof, will lead to the following expression (B9).

[Expression 3]

$$\begin{bmatrix} r_1 \\ r_1^* \end{bmatrix} = \begin{bmatrix} \dfrac{b_1}{2} \\ 0 \end{bmatrix} \quad ...(B6)$$

$$\begin{bmatrix} r_2 \\ r_2^* \end{bmatrix} = \begin{bmatrix} 0 \\ r_2^* \end{bmatrix} \quad ...(B7)$$

$$z_2 = \frac{P}{4} = \frac{\pi}{2\sqrt{A}} \quad ...(B8)$$

$$\begin{bmatrix} r_2 \\ r_2^* \end{bmatrix} = \begin{bmatrix} 0 & \dfrac{1}{n_1\sqrt{A}} \\ -n_1\sqrt{A} & 0 \end{bmatrix} \begin{bmatrix} \dfrac{b_1}{2} \\ 0 \end{bmatrix} \quad ...(B9)$$

The angle θ_{NA0} with respect to the optical axis on the

outgoing surface in the optical waveguide is given from the expression (B9).

$$r_2{}^* = \tan\theta_{NAO} = -n_1 \times \sqrt{A} \times b_1/2 \quad \ldots (B10)$$

Therefore, from the expression (B10), assuming that θ_{NAO} is a positive value, θ_{NAO} is given by the following expression.

$$\theta_{NAO} = \tan^{-1}(n_1 \times \sqrt{A} \times b_1/2) \quad \ldots (B11)$$

The outgoing angle θ'_{NAO} of this light to the air layer satisfies the relation of the following expression by applying Snell's Law to the outgoing surface on the optical axis.

$$n_{air} \times \sin\theta'_{NAO} = n_1 \times \sin\theta_{NAO} \quad \ldots (B12)$$

Here, n_{air} represents the refractive index of air.

From the expressions (B11) and (B12), the NA of the optical waveguide of the gradient index type is given by the following expression.

$$NA = \sin\theta'_{NAO} = (n_1/n_{air}) \times \sin\{\tan^{-1}(n_1 \times \sqrt{A} \times b_1/2)\} \quad \ldots (B13)$$

Therefore, when fluctuations in the length of the optical waveguides of the gradient index type, $L_{zmax} - L_{zmin}$ is larger than $P/2$ and the fluctuations are uniform, light diffusion of the top hat type is brought out within the angle $\pm\theta'_{NAO}$ of the NA given by the expression (B13).

The analysis described above is for the case in which the optical axis of the optical waveguide of the gradient

index type coincides with the normal line of the film plane.

Subsequently, analysis will be made for the case in which the optical axis is inclined by an angle θ with respect to the normal line of the film plane. As shown in Fig. 19, when there exists the optical waveguide of the gradient index type inclined by θ in the film, the optical system in which the prisms of the same apex angle are arranged on the incident side and the outgoing side of the optical waveguide on the opposite direction is obtained. By obtaining the NA of this optical system, the top hat characteristics of the film configured by the optical waveguide of the gradient index type inclined by θ can be described.

Since the optical system shown in Fig. 19 has the same structure on the incident side and the outgoing side, analysis is made on the outgoing side. θ_{NAO} in Fig. 19 is given by the expression (B11). When Snell's Law is applied to the optical axis of the optical waveguide of the gradient index type and the boundary portion with respect to the prism on the outgoing side, the following expression is obtained,

$n_1 \times \sin\theta_{NAO} = n_g \times \sin\theta_{g1}$ .... (B14)

,where n_g represents the refractive index of the prism.

Subsequently, focusing attention on the light $beam_1$ which travels upward, when Snell's law is applied to the

boundary where this light beam goes out from the prism to the air layer, the following expression is obtained.

$$n_g \times \sin(\theta + \theta_{g1}) = n_{air} \times \sin\theta_{NA1} \quad \ldots\text{(B15)}$$

Subsequently, focusing attention on the light $beam_2$ which travels downward, when Snell's Law is applied to the boundary where it goes out from the prism to the air layer, the following expression is obtained.

$$n_g \times \sin(\theta - \theta_{g1}) = n_{air} \times \sin\theta_{NA2} \quad \ldots\text{(B16)}$$

When $\sin\theta_{g1}$ is obtained by substituting θ_{NA0} in the expression (B11) into the expression (B14), the following expression is obtained.

$$\sin\theta_{g1} = (n_1/n_g) \times \sin\{\tan^{-1}(n_1 \times \sqrt{A} \times b_1/2) \quad \ldots\text{(B17)}$$

When θ_{NA1} and θ_{NA2} are obtained from the expressions (B15) and (B16) with $n_{air} = 1.0$, the following expressions are obtained respectively.

$$\theta_{NA1} = \sin^{-1}\{n_g \times \sin(\theta + \theta_{g1})\} \quad \ldots\text{(B18)}$$

$$\theta_{NA2} = \sin^{-1}\{n_g \times \sin(\theta - \theta_{g1})\} \quad \ldots\text{(B19)}$$

Therefore, since this optical system has the same structure on the incident side and the outgoing side, the angles of the NA of the input and output are represented by the following expressions.

$$\theta_{NA2} \leq \theta_{in} \leq \theta_{NA1} \quad \ldots\text{(B20)}, \quad \theta_{NA2} \leq \theta_{out} \leq \theta_{NA1} \quad \ldots\text{(B21)}$$

The angle of meandering of light in the optical waveguide falls within the range between $\theta - \theta_{NA0}$ and $\theta + \theta_{NA0}$, since the optical axis is inclined by θ. When θ_{NA0} in the

expression (B11) is substituted thereto, the following expression is obtained.

$$\theta - \tan^{-1}(n_1 \times \sqrt{A} \times b_1/2) \sim \theta + \tan^{-1}(n_1 \times \sqrt{A} \times b_1/2) \quad \dots (B22)$$

Since the optical axis is inclined by θ, the length of fluctuations is changed to $\cos\theta$ times of the length when $\theta = 0°$, and hence $L_{zmax} - L_{zmin}$ is given by the following expression.

$$L_{zmax} - L_{zmin} \geq (P/2) \times \cos\theta \quad \dots (B24)$$

Derivation and description of the expression for the layers of the film (2) having the refractive index distribution in Fig. 7(a) is now ended.

On the other hand, the refractive index distribution in Fig. 7(b) is different from that of the optical waveguide of the gradient index type to some extent. However, since this can also bring out the light-collecting property (the light-collecting property to keep the incident light within the layer) in the direction of the layer thickness, it can be treated in the same manner as the case of the optical waveguide of the gradient index type, and the desired diffuse light intensity distribution characteristics can be obtained by varying the existential probability of the layer length.

Even in the case in which the optical waveguides of the gradient index type having different refractive index

distributions from point to point are formed in the film, it can be treated in the same manner.

In the film (2), the diffuse light intensity distribution characteristics of the outgoing light is determined by the direction of light propagation within the layer and the existential probability of the layer length. Although the existential probability of the layer length is assumed to be distributed in the top hat shape in the example shown above in order to cause the incident light to be diffused in the distribution of the light intensity of the top hat type, however, by causing either one or both of the refractive index distribution within the layer and the existential probability according to the theory based on the same physical laws, desired diffuse light intensity distribution characteristics other than those of the top hat type (for example, the trapezoidal type, the Gaussian distribution, and so on) can also be obtained.

Although the film having no fluctuation in layer inclination angle is shown in Figs. 5 to 6, desired diffuse light intensity distribution characteristics may be obtained by making the angle of layer inclination in the direction in the plane fluctuated and changing the existential probability of the layer inclination angle as in the case of the film (1).

Although the surface of the film is planer in the

example shown in Fig. 5 and Fig. 6, even when the film

surface is a curved surface, it can be treated in the same

manner by considering it to be a group of minute planes.

Although the case in which the adjacent layers are in

contact with each other is shown in Fig. 5 and Fig. 6, it

can be treated in the same manner even when the adjacent

layers are separated by some extent. In this case, however,

part of the incident light is not propagated within the

layer, and travels along the portion in the film (2) where

the refractive index is constant (n_g), and hence the

percentage of the light which travels straight ahead is

increased.

Although the film plane on one side is the incident

side in Fig. 5 and Fig. 6, it can be treated in the same

manner even when the film plane on the opposite side is

employed as the incident side.

Subsequently, diffusion film (film (3), film (4), and

film (5)) stated in Claims 6 to 7 will be described. They

have a structure in which the structure of the film (1) and

the structure of the film (2) are combined.

Fig. 12(a) is a pattern diagram showing an example of

the film (3). As shown in the same drawing, a film (3) 53

has a structure in which a part 53_1 having the same

structure as the film (1) and a part 53_2 having the same

structure as the film (2) are mixed in the direction of the

film thickness.

Fig. 12(b) is a pattern diagram showing an example of the film (4). As shown in the same drawing, a film (4) 54 has a structure in which a part 54_1 having the same structure as the film (1), and a part 54_2 having the same structure as the film (2) are mixed in the direction of the film plane.

Fig. 12(c) is a pattern diagram showing an example of the film (5). As shown in the same drawing, a film (5) 55 has the same structure 55_A in which the structure of the film (1) and the structure of the film (2) are fused with each other.

In any of the diffusion films shown in Fig. 12, they can be treated as the respective film (1) and film (2) in the decomposed state, and the angular range of diffusion of the incident light is derived by superimposing the respective films.

Claims 8 to 16

Subsequently, Claims 8 to 16 will be described.

In a rear projection display system (abbreviated as "rear pro"), in order to reduce the thickness of the system, as shown in Fig. 33, for example, an optical engine (projector) 20 is arranged on the lower side of a screen 10, the direction of a light is changed by mirrors (mirrors M1, M3, a non-spherical mirror M2) or the like, and images

formed in an oblique direction from the lower side of the screen 10 with respect to a normal line of the screen are used. Therefore, since the diffusion characteristic in this structure is such that the center of a light energy is directed toward the upper side of the screen, a prism 30 (prism sheet) is generally used to direct the center of light intensity toward the normal line of the screen in the related art as shown in Fig. 32.

However, when the prism sheet is used in the thin-type rear-pro, there arise problems such as fluctuation of characteristics due to joint usage of the refraction type and reflection type, and difficulty in manufacture due to the difference in prism shape depending on the location to be provided.

In order to overcome such problems, the present invention employs a light-outgoing direction converting film 2 including a plurality of layers 1 which constitute light waveguide arrays arranged in the direction in the film plane in a striped state and extend so as to be bent with respect to the direction of the film thickness instead of the prism sheet in the related art as shown in Fig. 22. Reference numeral 3 designates a diffusion film for causing a light incoming from an angular range of diffusion of the incident light to be diffused into the angular range of diffusion of the outgoing-light. The diffusion film 3 and the light

outgoing direction converting film 2 constitute the screen 10.

The optical waveguide 1 of the light-outgoing direction converting film 2 is an optical waveguide of a step index type or an optical waveguide of a type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness (for example, gradient index type).

Fig. 23 is a pattern diagram showing an example of a light-outgoing direction converting film in a case in which a curved optical waveguide array is of a step index type. Layers (cores) 1_A having a refractive index n_1 which constitute the optical waveguides 1 and layers (clads) 1_B having a refractive index n_2 ($n_1 > n_2$) are layered alternately in the direction in the film plane. Reference numeral 2_X designates remaining portion (film portion other than the optical waveguide 1). Boundaries between the layers 1_A and 1_B are inclined by an angle of $\theta_{bend-in}$ on the incident side and by $\theta_{bend-out}$ on the outgoing side with respect to the normal line of the film plane. Such an optical waveguide of the step index type can be designed in such a manner that an incident light beam 8 into the core 1_A is totally reflected on the layer boundary, while being propagated along a curve of the optical waveguide 1 in the core 1_A, and goes out with the direction of the center of

the light intensity directed in a desired direction (for example, in the direction of the normal line to the film plane) determined by $\theta_{bent-out}$.

Fig. 25 is a pattern diagram showing an example of the light-outgoing direction conversion film in the case in which the curved optical waveguide array is of a type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness. Layers 1_C having the distribution of refractive indexes that brings out the light-collecting property in the direction of the layer thickness are layered in the direction in the film plane to constitute the optical waveguide array. Reference numeral 2_X designates the remaining portion (film portion other than the optical waveguide 1). Boundaries of the layers 1_C are inclined by $\theta_{bend-in}$ on the incident side and by $\theta_{bend-out}$ on the outgoing side with respect to the normal line to the film plane. The optical waveguide of the type having the distribution of refractive indexes that brings out the light-collecting property in the direction of the layer thickness can be designed in such a manner that the light beam 8 entered into the layer 1_C is propagated in the layer 1_C along the curve of the optical waveguide 1 while being refracted so as to draw a wave shape having an amplitude corresponding to the distance between the layers and goes out with the direction

of the center of the light intensity directed in the desired direction (for example, the direction of the normal line to the film plane) determined by $\theta_{bend-out}$.

A single sheet of the light-outgoing direction converting film may include only the optical waveguide of one of the step index type and the type having the distribution of the refractive indexes which brings out the light-collecting property in the direction of the layer thickness, or the optical waveguides of both types exist one or both of the direction in the film plane and the direction of the film thickness in a mixed manner. Fig. 26 show examples in which the optical waveguide array of the step index type and the optical waveguide array of the type having the distribution of refractive indexes which brings out the light-collecting property in the direction of the layer thickness exist in the direction of the film thickness in the mixed manner (a), and exist in the direction in the film plane in the mixed manner (b).

All the drawings and analysis disclosed in Claims 8 to 16 show examples in which the remaining portion 2_x having no layer formed therein exists. However, it is a portion which does not contribute directly to the light-outgoing direction converting property, and hence the light-outgoing direction converting property can be brought out also by the structure having no remaining portion 2_x or having the same only on

one side. This case can also be considered to be the same by considering the propagation of the light in the layers and calculating the refraction in the remaining portion 2_x when going out therefrom as in the case of an analysis shown below. Although the cross-section of the remaining portion 2_x in the direction of the layer thickness is a triangular shape and one side thereof is assumed to be an air interface of the film in the drawings, it can be considered to be the same even when it has other structure from the same reasons (for example, when the remaining portion 2_x is significantly large and there exists partly an range having no layer in the direction of the film thickness).

In the screen configured as described above, the light from the optical engine can be reflected or refracted in the curved optical waveguide and the direction of the center of the light intensity thereof can be directed to the desired direction (for example, in the direction of the normal line to the screen) determined by the $\theta_{bend-out}$. Accordingly, fluctuation of the characteristics due to the joint usage of the refracting type and the reflecting type and difficulty in manufacture due to the difference in prism shape depending on the location to be provided, as in the prism sheet in the related art, are diminished, and hence a light outgoing direction converting film which exerts superior characteristics such as:

6) ghost of an image due to a stray light is not generated;

7) the amount of rearward reflection is small;

8) efficiency of conversion of the light-outgoing direction is high;

9) there is no limit in the angle of conversion of the outgoing direction; and

10) polarization of an incident light is retained

can be realized.

As a matter of course, if the outgoing angular range of the light-outgoing direction converting film does not match the angular range of diffusion of the incident light of the diffusion film, part of the projector light does not diffuse in the direction in which the observer exists, and hence the usage efficiency of the projector light is lowered. Therefore, it is preferable that these angular ranges match, and at least it is necessary that 50 percent of the outgoing angular range θ_{out} of the light-outgoing direction converting film is included in the incident angular range of diffusion film $\theta_{bend-in}$.

Although the diffusion film to be used in combination with the light-outgoing direction conversion film is not specifically limited, the diffusion film used in Claims 1 to 7 is preferable.

The light-outgoing direction converting film may be converted into the light-outgoing direction

converting/diffusing film having substantially top hat shaped diffused light-intensity characteristics by distributing the layer inclination angle of the optical waveguide of the step index type and/or the length of the optical waveguide layers of the type having the distribution of the refractive indexes which brings out the light-collecting property in the direction of the layer thickness into substantially the top hat shape.

The light-outgoing direction converting/diffusing film corresponds to the diffusion film used in Claims 1 to 7 with the optical waveguides therein curved.

The single light-outgoing direction converting/diffusing film may includes only the optical waveguides of one of the step index type and the type having the distribution of refractive indexes which brings out the light-collecting property in the direction of the layer thickness or may includes the optical waveguides of both types in one or both of the direction in the film plane and the direction of the film thickness.

Further, the single light-outgoing direction converting/diffusing film may have a structure in which the optical waveguides of both types described above fused together. This structure has the distribution of refractive indexes in the layers is either one of a function of the distribution of refractive indexes of the step index type or

a function of the distribution of refractive indexes which brings out the light-collecting property in the direction of layer thickness, and includes the curved layers in which both of the layer inclination angle and the layer length are distributed so as to be fluctuated substantially in the top hat shape.

Since the light-outgoing converting/diffusing film has a function to diffuse the incident light with having bent in the optical waveguides, by using this film instead of the light-outgoing direction converting film (the light-outgoing direction converting film without the diffusing function), it is not necessary to use an additional diffusing film, and hence the screen can be configured only with the light-outgoing direction converting/diffusing film.

In the screen of Claims 8 to 14, the thickness of the respective layers forming the optical waveguides in the light-outgoing direction converting film or the light-outgoing direction converting/diffusing film is preferably smaller than 500 μm considering the size of pixels of the image projected by the general projection display, since images of high resolution cannot be propagated when it is too large.

The film plane of the light-outgoing direction converting film or the light-outgoing direction converting/diffusing film is not limited to a planer surface,

and may be a curved surface. In the case of the curved surface, it can be handled in the same manner by considering it to be a group of minute planes.

When constituting the optical system for projection display system using the screen of Claims 8 to 14, matching of an aperture (= Numerical Aperture: abbreviated as NA) with the optical engine is important. The NA of the optical engine is defined as NA = $\sin\theta_2$ where the angular range of a light beam incoming from behind the screen determined by the lens diameter, the focal length, the image-forming magnification, and the image-forming position of the optical engine 20 is assumed to be $2\theta_2 (\equiv 2 \times \theta_2)$ as shown in Fig. 22 relating the case of the rear projection display, for example.

In the actual optical system for projection display system, the optical element such as a reflective mirror or a lens is arranged between the optical engine and the screen in many cases as shown in Fig. 33, for example. In such a case, the NA is defined in the same manner in the drawing in which the optical system is converted into an optically equivalent mode using only one lens as shown in Fig. 22 or Fig. 27.

Assuming that a light emitted from an object (for example, an image display panel such as a liquid crystal or a DMD or the like in the projection display) 21 having a

length of S_1 placed at a distance "a" behind a lens of "d" in diameter and "f" in focal length as shown in Fig. 27 passes through the lens and forms an image at a distance "b" which satisfies the expression $1/a + 1/b = 1/f$ in front of the lens, the length S_2 of the image satisfies the expression $S_2/S_1 = b/a$, and assuming that the distances from the center axis of the lens to the lower end and the upper end of the image are l_1, l_2 respectively, and the angles formed by straight lines connecting between the upper end of the lens and the lower end of the image, and between the lower end of the lens and the upper end of the image with respect to the center axis of the lens are θ_0, θ_1 respectively, the angular range $2\theta_2$ corresponding to the NA is represented by the following expression.

$$2\theta_2 = \theta_1 - \theta_0 \qquad \ldots\ldots(0\text{-}1)$$
$$\tan\theta_1 = (l_2+d/2)/b \qquad \ldots\ldots(0\text{-}2)$$
$$\tan\theta_0 = (l_1-d/2)/b \qquad \ldots\ldots(0\text{-}3)$$

If all the light in the angular range $2\theta_2$ cannot be bent in the curved optical waveguides (hereinafter, referred to as bent waveguides), the usage efficiency of the screen light is lowered. In addition, the light leaked from the bent waveguides is led to lowering of the resolution of the image. Therefore, matching between the angular range $2\theta_2$ of the input light beam from behind the screen and the angular range corresponding to the NA of the bent waveguides is very

important in terms of design of the optical system for projection display system.

Therefore, the theoretical derivation of the NA of the bent waveguides will be described in detail below.

[NA of the bent waveguides of the step index type]

Fig. 28 shows a curved structure model of the step index type optical waveguide. It has a structure in which the layers (core) 1_A having the refractive index n_1 which constitute bent waveguides and the layers (clad) 1_B having a refractive index n_2 which is smaller than n_1 are alternately layered. The core 1_A is assumed to have the thickness y_1, the center of curvature O, and the radius of curvature r_o of the interface surface on the inner peripheral side. In this model, in order to make the NAs of the input and output easy to understand, linear structures (L portions) of minute length Δz are added to an entrance and an exit of a bent structure (C portion) of the optical waveguides. The external portion of the optical waveguide is an air layer having a refractive index n_{air}.

The light beams 5, 6 are in modes which can be propagated in the core 1_A of the C portion. These two modes are modes which are propagated by being totally reflected at a critical angle θ_c on an interface of the core 1_A of the C portion with respect to the clad 1_B on the outer peripheral side (outer interface), and at $\theta_c + \theta_r$ on an interface of the

core 1_A of the C portion with respect to the clad 1_B on the

inner peripheral side (inner interface). A light beam 5 is

propagated by being totally reflected at the critical angle

θ_C on the outer interface at the entrance and the exit of the

C portion, and a light beam 6 is propagated by being totally

reflected at a critical angle of $\theta_C + \theta_r$ on the inner

interface at the entrance and the exit of the C portion.

When the light beam 5 is totally reflected at the

entrance and the exit of the outer interface exactly at the

critical angle, outgoing angles into the air layer are θ_{in1}

and θ_{out1} in the drawing. When the position is slightly

shifted, since the total reflection is not effected exactly

at the entrance and the exit, the angles are $-\theta_{in1}$ and $-\theta_{out1}$.

Therefore, the NA of the mode of the light beam 5 is

determined by $\pm\theta_{in1}$ and $\pm\theta_{out1}$. When the same discussion is

made for the mode of the light beam 6, it can be said that

the NA of the mode is determined by $\pm\theta_{in2}$ and $\pm\theta_{out2}$.

We now focus attention on the light beam 5. Although

the drawing shows a light beam incoming at an angle of $+\theta_{in1}$,

a light entering into the entrance on the outer interface at

an angle of $-\theta_{in1}$ is considered (Δz is infinitely small).

The light entering into the entrance on the outer interface

can be propagated in the core of the C portion. However,

when the incoming position is moved from the outer interface

to the inner interface, the light beam is totally reflected

at the critical angle θ_c on the inner interface, and when it reaches the outer interface, it enters into the outer interface at an angle smaller than the critical angle θ_c, and hence the light does not totally reflect and refract into the clad. Therefore, in the case of the light beam 5, although the NA on the outer interface at the entrance and the exit are determined by $\pm\theta_{in1}$ and $\pm\theta_{out1}$, the NA is reduced as it approaches the inner periphery, and at the position on the inner interface, they coincide with the angles $\pm\theta_{in2}$ and $\pm\theta_{out2}$ which determine the NA of the light beam 6. Therefore, it can be said that the NA that allows safe propagation through the waveguides of curved structure is determined by the angles $\pm\theta_{in2}$ and $\pm\theta_{out2}$ of the light beam 6. Therefore, the design of the screen is discussed by these angles.

Subsequently, referring to Fig. 28, these angles $\pm\theta_{in2}$ and $\pm\theta_{out2}$ will be derived. A sine theorem is applied to a triangle OAB in Fig. 28; The following expression is obtained.

$$r_0/\sin\theta_c = (r_0 + y_1)/\sin\{\pi - (\theta_c + \theta_r)\} \qquad \dots(1\text{-}1)$$

Since θ_c is the critical angle, using the refractive indexes n_1, n_2 of the core and the clad, the following expression is obtained.

$$\theta_c = \sin^{-1}(n_2/n_1) \qquad \dots(1\text{-}2)$$

From the expressions (1-1), (1-2), the following expression is obtained.

$$\theta_c + \theta_r = \sin^{-1}\{(n_2/n_1) \times (1 + y_1/r_0)\} \qquad \ldots (1-3)$$

Therefore, Snell's Law of the following expression is established for the interface between the air layer and the optical waveguide wherein the light beam 6 is totally reflected at the point B.

$$n_{air} \times \sin\theta_{in2} = n_1 \times \sin\{\pi/2 - (\theta_c + \theta_r)\} \qquad \ldots (1-4)$$

From the expressions (1-2), (1-4), $\theta_{in2}(=\theta_{out2})$ are given by the following expression.

$$\theta_{in2} = \theta_{out2} = \sin^{-1}[(n_1/n_{air}) \times \cos\{\sin^{-1}((n_2/n_1) \times (1 + y_1/r_0))\}] \qquad \ldots (1-5)$$

Therefore, the input/output angle θ_{NAstep} with respect to the optical axis of the light which allows safe propagation without depending on the input position in the curved structure model of the step index optical waveguide shown in Fig. 28 is given by the following expression from the expression (1-5).

$$-\theta_{in2} \ (= -\theta_{out2}) \leq \theta_{NAstep} \leq +\theta_{in2} \ (= +\theta_{out2}) \qquad \ldots (1-6)$$

Subsequently, an NA in the case where the model shown in Fig. 28 is formed in the film having a refractive index n_g is obtained. Since the output side is perpendicular to the film plane, the NA whose output angle is $\pm\theta_{out2}$ in the expression (1-5) is obtained. On the input side, a prism (P portion) having the refractive index n_g, which corresponds to the remaining portion 2_X in Fig. 23, Fig. 25, and Fig. 26 is added. Such a state is shown in Fig. 29 and Fig. 30.

The light beam 6 which is totally reflected on the inner interface at the entrance and the exit of the C portion is shown in Fig. 29, and a light beam 7 which is not totally reflected is shown in Fig. 30. For the sake of easy understanding, L portions of Δz in length are added to the entrance and the exit of the C portion in Fig. 29. Actually, it may be considered as $\Delta z \rightarrow 0$.

The θ_{in4} in Fig. 29 is obtained in the following expression, by applying Snell's Law on the interface between the air layer and the P portion as regards the light beam 6.

$$n_{air} \times \sin(-\theta_{in4}) = n_g \times \sin(\theta_{bend} - \theta_{in3}) \quad \ldots \ldots (1-7)$$

Since θ_{in3} corresponds to θ_{in2} in the case in which n_{air} is replaced by n_g in Fig. 28, by changing the n_{air} into n_g in the expression (1-5), the following expression is obtained.

$$\theta_{in3} = \sin^{-1}[(n_1/n_g) \times \cos(\sin^{-1}((n_2/n_1) \times (1 + y_1/r_0)))] \quad \ldots \ldots (1-8)$$

From the expressions (1-7), (1-8),

$$-\theta_{in4} = \sin^{-1}[(n_g/n_{air}) \times \sin\{-\sin^{-1}((n_1/n_g) \times \cos(\sin^{-1}((n_2/n_1) \times (1 + y_1/r_0)))) + \theta_{bend}\}] \ldots \ldots (1-9)$$

is obtained.

Subsequently, θ_{in5} in Fig. 30 will be obtained. This can be obtained simply by changing the sign before θ_{bend} in the expressions (1-7) and (1-9), the following two expressions are established with corresponding to the expressions (1-7) and (1-9).

$n_{air} \times \sin(-\theta_{in5}) = n_g \times \sin(\theta_{bend} - \theta_{in3})$ ....(1-10)

$\theta_{in5} = \sin^{-1}[(n_g/n_{air}) \times \sin\{\sin^{-1}((n_1/n_g) \times \cos(\sin^{-1}((n_2/n_1) \times (1 + y_1/r_0))))+\theta_{bend}\}]$ ....(1-11)

Therefore, from the description above, the angle $\theta_{NAstepin}$ which determines the NA on the incident side of the film as the curved structure model of the step index optical waveguide and the angle $\theta_{NAstepout}$ which determines the NA on the outgoing side thereof are given by the following two expressions.

$\theta_{in4} \leq \theta_{NAstepin} \leq \theta_{in5}$ ....(1-12)

$-\theta_{out2} \leq \theta_{NAstepout} \leq \theta_{out2}$ ....(1-13)

On the other hand, from Fig. 29 and Fig. 30, since $-\theta_{in4} \geq -90°$, $\theta_{in5} \leq 90°$, from the expressions (1-9), (1-11), conditions of the layer inclination angle on the incident side θ_{bend} (hereinafter, represented as $\theta_{bend-in}$) are represented by the following expression.

$|\theta_{bend-in}| \leq -\sin^{-1}[(n_1/n_g] \times \cos\{\sin^{-1}((n_2/n_1) \times (2 \times R_{in} + y_1)/(2 \times R_{in} - y_1))\}] + \sin^{-1}(n_{air}/n_g)$ ....(1-14)

where R_{in} represents a radius of curvature at the center portion of the core thickness near the incoming surface (= $r_0 + y_1/2$).

In Fig. 28, if $|\theta_c + \theta_r| > \pi/2$, since the light beam 5 cannot totally reflect on the inner interface, $|\theta_c + \theta_r| \leq \pi/2$ is a prerequisite of the model, and from this condition and the expression (1-3), $r_0 \leq n_2/(n_1 - n_2) \times y_1$. Therefore,

the radius of curvature at the center portion of the core thickness of the curved waveguide must be at least a minimum radius of curvature $R_{minstep}$ which is given by the following expression.

$R_{minstep}$ = n₂/(n₁ − n₂) × y₁ + y₁/2 = (n₁ + n₂)/(n₁ − n₂) × (y₁/2)   ....(1-16)

From the description above, in the case of the bent waveguides of the step index type, a light entered into the bent waveguides at a certain incoming angle within the incoming angular range (θ_{in-min} to θ_{in-max}) is gradually changed in its direction of propagation in the bent waveguides and goes out at a certain outgoing angle within the outgoing angular range ($\theta_{out-min}$ to $\theta_{out-max}$). θ_{in-min}, θ_{in-max}, $\theta_{out-min}$, $\theta_{out-max}$ are given by the following expressions.

[Expression 4]

$$\theta_{in-min} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{-\sin^{-1}\left(\frac{n_1}{n_g}\cos\left(\sin^{-1}\left(\frac{n_2}{n_1}\cdot\frac{2R_{in}+y_1}{2R_{in}-y_1}\right)\right)\right)+\theta_{bend-in}\right\}\right] \quad ...(1-17)$$

$$\theta_{in-max} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{\sin^{-1}\left(\frac{n_1}{n_g}\cos\left(\sin^{-1}\left(\frac{n_2}{n_1}\cdot\frac{2R_{in}+y_1}{2R_{in}-y_1}\right)\right)\right)+\theta_{bend-in}\right\}\right] \quad ...(1-18)$$

$$\theta_{out-min} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{-\sin^{-1}\left(\frac{n_1}{n_g}\cos\left(\sin^{-1}\left(\frac{n_2}{n_1}\cdot\frac{2R_{out}+y_1}{2R_{out}-y_1}\right)\right)\right)+\theta_{bend-out}\right\}\right] \quad ...(1-19)$$

$$\theta_{out-max} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{\sin^{-1}\left(\frac{n_1}{n_g}\cos\left(\sin^{-1}\left(\frac{n_2}{n_1}\cdot\frac{2R_{out}+y_1}{2R_{out}-y_1}\right)\right)\right)+\theta_{bend-out}\right\}\right] \quad ...(1-20)$$

In the models shown in Fig. 28 to Fig. 30, the layer interface from the entrance to the exit of the waveguides

for all the optical paths are curved lines having no abrupt
change in angle. In this case, the incoming light is not
diffused, and only the outgoing direction is converted. On
the other hand, according to the present invention, the
layer interface can be adapted to be a curved line whose
angle is abruptly changed. In this case, the direction of
reflection of the incoming light may be changed in the layer,
so that the incoming light can be diffused while being
changed in direction of travel. In the present invention,
the phrase "the radius of curvature is fluctuated from point
to point to diffuse the incoming light" unless otherwise
specified indicates the case in which the layer inclination
angle is a curved line whose angle is abruptly changed, and
the term "abrupt change in the layer inclination angle"
means the change in layer inclination angle at least 0.01
deg./μm.

[NA of the bent waveguides of the gradient index type]

According to the theoretical analysis of the inventors,
when the curved line of the bent waveguides of the gradient
index type is approximated by a polygonal line, the error of
the radius of curvature by the approximation is as small as
1.3% when the refractive index at the center portion of the
width (layer thickness) of the bent waveguides is 1.55,
which is close to a core value of the general optical
waveguides. Therefore, in the description below, the NA is

derived by the polygonal approximation model.

The linear portion in the polygonal approximation model is a linear gradient index optical waveguide 4, whose distribution of the refractive indexes in the direction of the layer thickness as shown in Fig. 34 is represented by a curve of second order:

$$n(r) = n_1 \times (1 - A/2 \times r^2) \qquad \ldots\ldots(2-1)$$

where r represents a distance from the center of the layer thickness, and n_1 represents a refractive index on the center axis. A represents a refractive index distribution constant, and is represented by

$$A = (8/y_1^2) \times (n_1-n_2)/n_1 \qquad \ldots\ldots(2-2)$$

by n_1, the layer thickness y_1, and the refractive index n_2 at the end of the layer thickness.

As shown in the drawings, assuming that the length of the waveguide is z, positions of the input light beam and the output light beam are r_1, r_2, directions of the light beam within the waveguide at the respective positions are $r_1^* = dr_1/dz = \tan \theta_{in}$, $r_2^* = dr_2/dz = \tan\theta_{out}$, the following expression (2-3) is established between vectors $[r_1, r_1^*]$, $[r_2, r_2^*]$ representing the position and the direction of the input light beam and output light beam.

[Expression 5]

$$\begin{bmatrix} r_2 \\ r_2^* \end{bmatrix} = \begin{bmatrix} \cos\left(\sqrt{A}z\right) & \dfrac{\sin\left(\sqrt{A}z\right)}{n_1\sqrt{A}} \\ -n_1\sqrt{A}\sin\left(\sqrt{A}z\right) & \cos\left(\sqrt{A}z\right) \end{bmatrix} \begin{bmatrix} r_1 \\ r_1^* \end{bmatrix} \qquad ...(2-3)$$

In the expression (2-3), if the matrix term of 2×2 is a unit matrix, the [position, direction] vector is the same between the input light beam and the output light beam. The minimum solution of the length z at this time is referred to as a pitch P of the waveguide, and factors of the matrix term are functions of sine and cosine. Therefore, the expression

$$P = 2 \times \pi/\sqrt{A} \qquad ....(2-4)$$

is established.

The angle that determines the NA of the linear gradient index optical waveguide is given by the largest angle out of the angle between the light beam that can be propagated in the waveguide and the optical axis (z-axis). As shown in Fig. 35, the largest angle corresponds to the angle θ_{NAO} between the output light beam and the optical axis (negative when y_1 is + and positive when y_1 is -) in the case where the length of the waveguide is P/4, and the [position, direction] vectors of the input light beam and the output light beam are $[\pm y_1/2, 0]$, $[0, r_2^*]$. The angle θ_{NAO} is obtained by substituting 0 for r_2, $-y_1/2$ for r_1, 0 for r_1^*, and P/4 = $\pi/(2 \times \sqrt{A})$ for z into the expression (2-3), and obtaining the value r_2^* (= $\tan\theta_{NAO}$), which is represented by

the expression;

$$\theta_{NA0} = \tan^{-1}(n_1 \times \sqrt{A} \times y_1/2) \qquad \dots \dots (2-5)$$

Fig. 36 shows a polygonal approximation model. This is an approximation of the bent waveguide of the gradient index type obtained by the optical waveguides of a polygonal gradient index type in which a structure such that the above-described linear gradient index optical waveguide is bent by an angle θ_{NA0}/n (n is a real number equal to or larger than 0.5) at a position of the length $P/2$, and then by an angle θ_{NA0}/n at a position proceeded by $P/2$ in the direction of the optical axis is repeated. Light beams 15, 16, 17, 18 in the drawing indicate modes of the representative light beam which can be propagated in the polygonal optical waveguide. When n is smaller than 0.5, since the light goes out from the waveguide, it is excluded from the object of the model.

The light beam 17 is a light incoming in parallel with the optical axis of the first linear gradient index optical waveguide 4_1 (hereinafter, referred to as the optical waveguide 4_1) to a position of the optical axis, and this light travels straight ahead in the optical waveguide 4_1, and then enters into the second linear gradient index optical waveguide 4_2 (hereinafter, referred to as the optical waveguide 4_2) which is inclined by $-\theta_{NA0}/n$ at a position advanced by $P/2$. Therefore, the incident angle

into the optical waveguide 4_2 is θ_{NA0}/n. Since the lengths of the respective linear gradient index optical waveguides are $P/2$, the outgoing angle of the optical waveguide 4_2 is $-\theta_{NA0}/n$ with respect to the optical axis of the optical waveguide 4_2. Since the third linear gradient index optical waveguide 4_3 (hereinafter, referred to as the optical waveguide 4_3) is inclined by $-\theta_{NA0}/n$ with respect to the second optical waveguide 4_2, the incident angle of the light beam 7 is $0°$, and hence the light beam 17 travels straight ahead in the linear gradient index optical waveguide of the odd number sequence, and changes the direction of travel and curved from the incident angle: $+\theta_{NA0}/n$ to the outgoing angle: $-\theta_{NA0}/n$ in the linear gradient index optical waveguide of the even number sequence. On the other hand, the light beam 16 shows a mode in which the state in the linear gradient index optical waveguides of the odd number sequence and the even number sequence of the light beam 17 are exchanged.

The light beams which determine the NA of the polygonal gradient index optical waveguide are the light beam 15 and the light beam 18.

The light beam 15 is a light beam of the maximum possible incident angle which can be propagated in the optical waveguide 4_1. Therefore, the incident angle into the waveguide of the optical waveguide 4_1 is θ_{NA0}. Since the lengths of the respective linear gradient index optical

waveguides are P/2, the outgoing angle of the light beam 15
from the optical waveguide 4_1 is $-\theta_{NA0}$. Since the optical
waveguide 4_2 is inclined by $-\theta_{NA0}/n$ with respect to the
optical waveguide 4_1, the incoming angle of the light beam
15 with respect to the optical axis of the optical waveguide
4_2 is $-(1 - 1/n) \times \theta_{NA0}$. Since the absolute value of the
incident angle: $|(1 - 1/n) \times \theta_{NA0}|$ is smaller than θ_{NA0}, the
light beam 15 can be propagated within the optical waveguide
4_2. Since the length of the optical waveguide 4_2 is also P/2,
the outgoing angle with respect to the optical axis of the
optical waveguide 4_2 is $(1-1/n) \times \theta_{NA0}$. Since the optical
waveguide 4_3 of the next sequence is inclined by $-\theta_{NA0}/n$ with
respect to the optical waveguide 4_2, the incident angle of
the light beam 15 with respect to the optical waveguide 4_3
is θ_{NA0}, which is the same light propagation state in the
optical waveguide 4_1. Therefore, the light beam 15 is a
mode in which the direction is changed from the incident
angle: θ_{NA0} to the outgoing angle: $-\theta_{NA0}$ in the linear
gradient index optical waveguide of the odd number sequence,
and from the incident angle: $-(1-1/n) \times \theta_{NA0}$ to the outgoing
angle: $(1-1/n) \times \theta_{NA0}$ in the linear gradient index optical
waveguide of the even number sequence, before propagation.
In other words, the mode shown in conjunction with the light
beam 15 is a mode of the maximum possible incident angle
which can be propagated within the linear gradient index

optical waveguide of the odd number sequence. On the other hand, the light beam 18 represents a mode in which the state in the linear gradient index optical waveguides of the odd number sequence and the even number sequence of the light beam 15 are exchanged. Therefore, the NA of the polygonal gradient index optical waveguide is determined by an angle between the incident angle and the outgoing angle of the light beam 15 and by an angle between the incident angle and the outgoing angle of the light beam 18.

Subsequently, the NA will be obtained. Assuming that the number of the linear gradient index optical waveguides which constitute the polygonal model is a natural number k, an optical axis of the kth linear gradient index optical waveguide is bent by an angle θ_{bend}, which is represented by the following expression, with respect to that of the first linear gradient index optical waveguide.

$$\theta_{bend} = -(k-1) \times \theta_{NAO}/n \qquad \ldots (2-6)$$

The angle $\theta_{NAO}(k)$ which determines the NA of the outgoing side in the kth linear gradient index optical waveguide is given by following expression, from Fig. 36,

$$\theta_{bend} - \theta_{NAO} \leq \theta_{NAO}(k) \leq \theta_{bend} + (1 - 1/n) \times \theta_{NAO} \qquad \ldots (2-7)$$

and the following expression is obtained by substituting the expression (2-6) into about expression (2-7).

$$-\theta_{NAO}/n \times (k+n-1) \leq \theta_{NAO}(k) \leq -\theta_{NAO}/n \times (k - n) \qquad \ldots (2-8)$$

Since the natural number k exists in the angle represented by the expressions (2-6), (2-7), and (2-8), it is a discrete angle definition. However, the polygonal approximation model in Fig. 36 is an approximation of the bent waveguide existing in the actual film. Therefore, even when the entire model is continuously rotated about the center of the curvature of the polygonal approximation model in Fig. 36, the NA of the model does not change, and the NA is determined by the radius of curvature and the refractive index distribution function $n(r)$ represented by the expression (2-1).

Therefore, θ_{bend} in the expression (2-7) can be treated as a continuous value, not as a discrete value. An angle θ_{NA1} which determines the NA in the optical waveguide of the polygonal approximation model in the case where the θ_{bend} is treated as the continuous value is given by the following expression.

$$\theta_{bend} - \theta_{NA0} \leq \theta_{NA1} \leq \theta_{bend} + (1 - 1/n) \times \theta_{NA0} \qquad \ldots (2-9)$$

When the model in Fig. 36 is formed in the film, as shown in Fig. 37, the prism (P portion) having a refractive index n_g and apex angle θ_{bend} which correspond to the remaining portion 2_x in Fig. 23, Fig. 25, and Fig. 26 are added to the outgoing portion on the right side.

When Snell's Law is applied to the interface between the outgoing end of the waveguide 4_4 and the P portion and

the interface between the P portion and the air layer (refractive index: n_{air}) for the light beam 18, the following expressions (2-10) and (2-11) are obtained respectively.

$$n_1 \times \sin\theta_{NA0} = n_g \times \sin\theta_{ng1} \quad\quad \ldots(2\text{-}10)$$

$$n_g \times \sin(\theta_{bend} + \theta_{ng1}) = n_{air} \times \sin\theta_{out1} \quad\quad \ldots(2\text{-}11)$$

From the expressions (2-10), (2-11), the θ_{out1} is obtained by the following expression.

$$\theta_{out1} = \sin^{-1}[n_g/n_{air} \times \sin\{\theta_{bend} + \sin^{-1}(n_1/n_g \times \sin\theta_{NA0})\}] \quad\quad \ldots(2\text{-}12)$$

When performing the same analysis for the light beam 15, the following two expressions are established.

$$n_1 \times \sin\{(1 - 1/n) \times \theta_{NA0}\} = n_g \times \sin\theta_{ng2} \quad\quad \ldots(2\text{-}13)$$

$$n_g \times \sin(\theta_{bend} - \theta_{ng2}) = n_{air} \times \sin\theta_{out2} \quad\quad \ldots(2\text{-}14)$$

From the expressions (2-13) and (2-14), θ_{out2} is given by the following expression.

$$\theta_{out2} = \sin^{-1}[n_g/n_{air} \times \sin\{\theta_{bend} - \sin^{-1}(n_1/n_g \times \sin((1 - 1/n) \times \theta_{NA0}))\}] \quad\quad \ldots(2\text{-}15)$$

From the expressions (2-12) and (2-15), the NA on the outgoing side is determined by the following θ_{NAout}.

$$-\theta_{out2} \leq \theta_{NAout} \leq -\theta_{NAout} \quad\quad \ldots(2\text{-}16)$$

The NA on the incident side is $\theta_{bend} = 0°$ in the expressions (2-12) and (2-15), and when θ_{out1} in the expression (2-12) is changed into θ_{in1}, and θ_{out2} in the expression (2-15) is changed into θ_{in2}, the following two expressions are established.

$\theta_{in1} = \sin^{-1}(n_1/n_{air} \times \sin\theta_{NA0})$ ....(2-17)

$\theta_{in2} = \sin^{-1}\{n_1/n_{air} \times -\sin((1 - 1/n) \times \theta_{NA0})\}$ ....(2-18)

From the expressions (2-12) and (2-15), the NA on the incident side is determined by θ_{NAin} in the following expression.

$\theta_{in2} \leq \theta_{NAin} \leq \theta_{in1}$ ....(2-19)

In the model shown in Fig. 36, although the input and output angles of the light are opposite to the case of the rear projection display system in Fig. 22, by changing the lower case "out" attached to the angle θ in the expressions (2-12), (2-15) and (2-16) into "in", the following three expressions in which the angle on the incident side matches the system in Fig. 22 are established.

$\theta_{in1} = \sin^{-1}[n_g/n_{air} \times \sin\{\theta_{bend} + \sin^{-1}(n_1/n_g \times \sin\theta_{NA0})\}]$ ....(2-12A)

$\theta_{in2} = \sin^{-1}[n_g/n_{air} \times \sin\{\theta_{bend} - \sin^{-1}(n_1/n_g \times \sin((1 - 1/n) \times \theta_{NA0}))\}]$ ....(2-15A)

$\theta_{in2} \leq \theta_{NAin} \leq \theta_{in1}$ ....(2-16A)

On the outgoing side, the following three expressions which match the system in Fig. 22 are established from the expressions (2-17), (2-18) and (2-19).

$\theta_{out1} = -\sin^{-1}(n_1/n_{air} \times \sin\theta_{NA0})$ ....(2-17A)

$\theta_{out2} = \sin^{-1}\{n_1/n_{air} \times \sin((1 - 1/n) \times \theta_{NA0})\}$ ....(2-18A)

$\theta_{out1} \leq \theta_{NAout} \leq \theta_{out2}$ ....(2-19A)

The expression (2-19A) represents the fact that when the optical axis of the optical waveguide is bent to the direction of the normal line of the screen, the NA on the outgoing side becomes asymmetry. Therefore, subsequently, the angle θ_{axis} of the optical axis of the optical waveguide on the outgoing side for causing the NA to be symmetry on the upper side and lower side on the outgoing side is obtained by analysis.

Fig. 38 shows an end portion of the last optical waveguide (linear gradient index optical waveguide) 4_L on the outgoing side, which is ended by an angle θ_{axis} of optical axis. The output NA is determined by the angle between the light beams 15 and 18. Therefore, the value of θ_{axis} when $\theta_{out3} = \theta_{out4}$ is established in the drawing corresponds to the angle of the optical axis to be obtained.

θ_{out3} will be obtained by the expression (2-22) from the expression (2-20) which is established on the interface between the outgoing surface of the optical waveguide and the P portion and the expression (2-21) established on the interface between the P portion and the air layer for the light beam 18.

$n_1 \times \sin\theta_{NA0} = n_g \times \sin\theta_{ng3}$ ....(2-20)

$n_g \times \sin(\theta_{ng3} - \theta_{axis}) = n_{air} \times \sin\theta_{out3}$ ....(2-21)

$\theta_{out3} = \sin^{-1}[n_g/n_{air} \times \sin\{\sin^{-1}(n_1/n_g \times \sin\theta_{NA0}) - \theta_{axis}\}]$ ....(2-22)

θ_{out4} is obtained from the expression (2-25) from the expression (2-23) established on the interface between the outgoing surface of the optical waveguide and the P portion and the expression (2-24) established on the interface between the P portion and the air layer for the light beam 15.

$$n_1 \times \sin\{(1 - 1/n) \times \theta_{NA0}\} = n_g \times \sin\theta_{ng4} \qquad \ldots\ldots(2-23)$$

$$n_g \times \sin(\theta_{ng4} + \theta_{axis}) = n_{air} \times \sin\theta_{out4} \qquad \ldots\ldots(2-24)$$

$$\theta_{out4} = \sin^{-1}[n_g/n_{air} \times \sin\{\sin^{-1}(n_1/n_g \times \sin((1-1/n) \times \theta_{NA0})) + \theta_{axis}\}] \qquad \ldots\ldots(2-25)$$

Therefore, from the expressions (2-22) = (2-25), θ_{axis} to be obtained is given by the following expression.

$$\theta_{axis} = 1/2 \times [\sin^{-1}(n_1/n_g \times \sin\theta_{NA0}) - \sin^{-1}(n_1/n_g \times \sin((1 - 1/n) \times \theta_{NA0}))] \qquad \ldots\ldots(2-26)$$

An angle which determines the NA on the outgoing side under the establishment of the expression (2-26) can be obtained by the following expression, by substituting the expression (2-26) into the expression (2-22) or the expression (2-25), herein an angle to be obtained is $\theta'_{out3} = \theta'_{out4}$.

$$\theta'_{out3} = \theta'_{out4} = \sin^{-1}[n_g/n_{air} \times \sin\{1/2 \times \sin^{-1}(n_1/n_g \times \sin((1 - 1/n) \times \theta_{NA0})) + 1/2 \times \sin^{-1}(n_1/n_g \times \sin\theta_{NA0})\}] \qquad \ldots\ldots(2-27)$$

Therefore, from the expression (2-27), an angle which determines the NA on the outgoing side which is symmetry on

the upper and lower sides is obtained by the following expression.

$$-\theta'_{out3} \leq \theta_{NAout} \leq \theta'_{out3} \qquad \ldots (2\text{-}28)$$

Subsequently, the radius of curvature of this model is derived. As shown in Fig. 39, in this polygonal approximation model, the center of curvature is an intersection O of perpendicular bisectors of the respective segments having a length P/2 of the linear gradient index optical waveguides 4_1, 4_2, 4_3, ..., and a radius of curvature R ($R = r_0 + y_1/2$ from the same drawing) is a distance from the center of curvature O to the center points of the length and the thickness of the respective optical waveguides 4_1, 4_2, 4_3, ... In the same drawing, when attention is focused on a right-angled triangle having the apex angle $\theta_{NA0}/(2 \times n)$, the following expression is established.

$$\tan(\theta_{NA0}/(2 \times n)) = (P/4)/(r_0 + y_1/2) \qquad \ldots (2\text{-}29)$$

From the expression (2-29), the radius of curvature R is given by the following expression.

$$R = r_0 + y_1/2 = (P/4)/\tan(\theta_{NA0}/(2 \times n)) \qquad \ldots (2\text{-}30)$$

In other words, when θ_{NA0} and P of the linear gradient index optical waveguide which are of the polygonal approximation model are obtained, and n (real number equal to or larger than 0.5) that determines the bent angle (bending extent) is determined, the radius of curvature is determined by the expression (2-30). The minimum radius of

curvature R_{min} is obtained by the following expression, when n = 0.5, and is given by an expression obtained by substituting 0.5 for n in the expression (2-30) and the expressions (2-4) and (2-5).

$$R_{min} = \pi/(n_1 \times A \times y_1) \quad \ldots (2-31)$$

In this case, the error of the polygonal approximation model becomes the maximum value. On the other hand, although detailed description of the process of derivation is omitted, the minimum radius of curvature R'_{min} of the optical waveguides of the gradient index type (curved structure model) having the same thickness and distribution of refractive index is given by the following expression.

$$R'_{min} = 2/(A \times y_1) \quad \ldots (2-32)$$

From the expressions (2-31) and (2-32), an error factor between the R'_{min} (corresponding to a rigorous solution) and the R_{min} (corresponding to an approximated solution) is $\pi/(2 \times n_1)$, and when 1.55, which is close to the core value of the general optical waveguide, is substituted for n_1, 1.0134 is obtained as the value of the error factor. Therefore, the error of the approximated solution with respect to the rigorous solution is within the 1.3% at the maximum, and hence the polygonal approximation model can be said to be sufficiently good approximation of the curved structure model.

Since the incident angle of the light is within the

range between -90° and 90° with respect to the normal line to the film plane, $\theta_{in2} \geq -90°$ and $\theta_{in1} \leq 90°$ are established in the expression (2-16A). From these constraints and the expressions (2-12A) and (2-15A), a condition of the layer inclination angle near the incident surface $\theta_{bend-in}$ are expressed by the following expression using the radius of curvature of the layer near the incident surface R_{in}, the angle of propagation in the layer θ_{NA0}, and the pitch P of the light propagation.

$$\theta_{bend-in-min} \leq \theta_{bend-in} \leq \theta_{bend-in-max} \quad \ldots\ldots (2-33)$$

$$\theta_{bend-in-min} = \sin^{-1}\{n_1/n_g \times \sin(\theta_{NA0} - 2 \times \tan^{-1}(P/(4 \times R_{in})))\} - \sin^{-1}(n_{air}/n_g) \quad \ldots\ldots (2-34)$$

$$\theta_{bent-in-max} = -\sin^{-1}(n_1/n_g \times \sin\theta_{NA0}) + \sin^{-1}(n_{air}/n_g) \quad \ldots (2-35)$$

Since the outgoing angle of the light is also within the range between -90° and 90° with respect to the normal line to the film plane, $\theta_{out2} \geq -90°$ and $\theta_{out1} \leq 90°$ are established in the expression (2-16). From these constraints and the expressions (2-12) and (2-15), a condition of the layer inclination angle near the incident surface $\theta_{bend-out}$ are expressed by the following expression using the radius of curvature of the layer near the incident surface R_{out}, the angle of propagation in the layer θ_{NA0}, and the pitch P of the light propagation.

$$-\theta_{bend-out-min} \leq \theta_{bend-out} \leq -\theta_{bend-out-max} \quad \ldots\ldots (2-36)$$

$\theta_{bend-out-min} = \sin^{-1}\{n_1/n_g \times \sin(\theta_{NA0} - 2 \times \tan^{-1}(P/(4 \times R_{out})))\} - \sin^{-1}(n_{air}/n_g)$ .... (2-37)

$\theta_{bent-out-max} = -\sin^{-1}(n_1/n_g \times \sin\theta_{NA0}) + \sin^{-1}(n_{air}/n_g)$ .... (2-38)

The lowest limit of the radius of curvature of the layer in the film is the value of the expression (2-32).

From the description above, in the bent waveguide of the gradient index type, the light incoming into the bent waveguide at a certain incident angle within the range of the incident angle (θ_{in-min} to θ_{in-max}) is changed gradually in the direction of propagation within the bent waveguide, and goes out at a certain outgoing angle within the range of the outgoing angle ($\theta_{out-min}$ to $\theta_{out-max}$). The θ_{in-min}, θ_{in-max}, $\theta_{out-min}$, $\theta_{out-max}$ are given by the following expression.

[Expression 6]

$$\theta_{in-min} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{-\sin^{-1}\left(\frac{n_1}{n_g}\sin\left(\theta_{NA0} - 2\tan^{-1}\frac{P}{4R_{in}}\right)\right)+\theta_{bend-in}\right\}\right] \quad ...(2-39)$$

$$\theta_{in-max} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{\theta_{bend-in} + \sin^{-1}\left(\frac{n_1}{n_g}\sin\theta_{NA0}\right)\right\}\right] \quad ...(2-40)$$

$$\theta_{out-min} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{-\sin^{-1}\left(\frac{n_1}{n_g}\sin\left(\theta_{NA0} - 2\tan^{-1}\frac{P}{4R_{out}}\right)\right)+\theta_{bend-out}\right\}\right] \quad ...(2-41)$$

$$\theta_{out-max} = \sin^{-1}\left[\frac{n_g}{n_{air}}\sin\left\{\theta_{bend-out} + \sin^{-1}\left(\frac{n_1}{n_g}\sin\theta_{NA0}\right)\right\}\right] \quad ...(2-42)$$

In the models shown in Figs. 34 to 39, it is assumed that the lengths of the plurality of layers are equivalent.

In this case, the incident light is not diffused, and only the outgoing direction is converted. On the other hand, in the present invention, the lengths of the individual layers can be varied. In this case, by varying the outgoing direction of the light which goes out from the layer for each layer, the light can be diffused while converting the direction of conversion of the incident light.

There may exist various types of the optical waveguide of the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness other than those having a parabola-shaped distribution of refractive indexes as the gradient index type, such as those having a substantially trapezoidal distribution of refractive indexes as shown in Fig. 40. In any cases, as long as they can propagate the incident light within the layer, the same outgoing direction converting characteristics as in the case of the gradient index type can be obtained.

Here, the radius of curvature is not necessarily required to be constant from the entrance to the exit of the waveguide both for the step index type and the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness. In the case of a gradual change such that the average inclination angle of the waveguide is less than 0.01 deg./μm

as well, the same light outgoing direction converting effects can be obtained. In the case of an abrupt change such that the angle of layer inclination is 0.01 deg./μm or higher in the step index type, the light-outgoing direction converting/diffusing diffusion film of the step index type is obtained as described above. In the case in which the layer inclination angle is rapidly changed by 0.01 deg./μm or more in the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness, a light-outgoing direction converting/diffusing film having a later-described "a structure in which the step index type and the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness are fused" is obtained.

Both in the step index type shown in Fig. 23 and the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness shown in Fig. 25, the adjacent layers are in contact with each other in the drawing. However, even though the adjacent layers are separated by some extent, they can be treated as those having the adjacent layers in contact with each other. In this case, however, the outgoing direction converting efficiency may be slightly lowered.

In the case in which the optical waveguide array of the step index type and the optical waveguide array of the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness are mixed in the direction of the thickness in the light outgoing direction converting film (Fig. 26-a), or in the case in which the optical waveguide array of the step index type and the optical waveguide array of the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness are mixed in the direction in a film plane or in the planar direction in the light-outgoing direction converting/diffusing film (Fig. 26-b), or in the case of the optical waveguide array having a structure in which both of the types are fused, the incident angle range and the outgoing angle range can be obtained by overlapping the derived results for each type.

[NA matching with the optical engine]

Subsequently, an NA matching between the light-outgoing direction converting film or the light-outgoing direction converting/diffusing film (hereinafter, referred to as the film of the present invention) which constitutes the screen of the present invention and the optical engine will be described.

A screen aperture angle θ_S is defined as $\theta_S \equiv \theta_{S-max} - \theta_{S-}$

$_{min}$ using the minimum aperture angle of screen θ_{S-min} and the maximum aperture angle of screen θ_{S-max}. In order to convert the light- outgoing direction of the projector to the direction of the observer by matching with the NA of the optical engine, θ_S must be at least $2\theta_2$ in Fig. 22 and Fig. 27. In other words, from the above-described expressions (0-1), (0-2) and (0-3), a condition is represented as follows.

$$\theta_S \geq \tan^{-1}\{(l_2 + d/2)/b\} - \tan^{-1}\{(l_2 + d/2)/b\} \quad \ldots (0-4)$$

Here, the case of the equal sign corresponds to the matched state. The above-described θ_{S-min} and θ_{S-max} are respectively equal to the lower limit θ_{in-min} and the upper limit θ_{in-max} of the incident angle range of the film of the present invention. These values may be obtained by the expressions (1-17) and (1-18) in the case of the step index type, and by (2-39), (2-40) in the case of the gradient index type.

When the optical waveguide array of the step index type and the optical waveguide array of the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness are mixed, preferably, the smaller one of the upper limits of the incident angle ranges of both types is employed as the θ_{S-max}, and the larger one of the lower limits of the incident angle ranges of both types is employed as the θ_{S-min}.

In other words, assuming that the lower limit and the upper limit of the incident angle range of the optical waveguide of the step index type are $\theta_{STEPin-min}$ and $\theta_{STEPin-max}$, and the lower limit and the upper limit of the incident angle range of the optical waveguide of the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness are $\theta_{GRADin-min}$ and $\theta_{GRADin-max}$, it is preferable to design the film so as to satisfy the following expression.

$$\text{Min}\{\theta_{STEPin-max}, \theta_{GRADin-max}\} - \text{Max}\{\theta_{STEPin-min}, \theta_{GRADin-min}\} \geq \tan^{-1}\{(l_2 + d/2)/b\} - \tan^{-1}\{(l_2 - d/2)/b\} \quad \ldots (0-5)$$

Although the discussion thus far is ideal that utilizes the projector light effectively, at least 50% of the light emitted from the optical engine in the numerical aperture NA must be enter into the screen from the range between θ_{min} and θ_{max} in the actual rear projection display as well.

[Method of manufacturing the film of the present invention]

Subsequently, a method of manufacturing a diffusion film used in Claims 1 to 7 will be described.

This diffusion film is obtained by irradiating light to a mixture including at least two or more different types of photo-polymerizable monomer or oligomer having different refractive indexes from two different directions for curing the same. The conditions of the irradiation of the light are adequate conditions which satisfy the requirements of

the present invention, and the adequate conditions are determined by an experiment.

The photo-polymerizable monomer or oligomer is monomer or oligomer having at least one polymerizable group such as acryloyl group, metaacryloyl group, or vinyl group in a particle. A mixture of a plurality of chemical compounds is applied on the substrate or encapsulated in the cell to obtain a film and cured gradually while irradiating light from two or more directions.

The light to be irradiated may have any wavelength as long as it can cure the compound which includes monomer or oligomer, and visible light beam or ultraviolet beam are often used.

The ultraviolet beam is irradiated by using a mercury lamp or a metal halide lamp or the like. However, when a rod-shaped lamp is used, by adjusting the conditions of irradiation, the obtained sheet like cured substance is caused to have anisotropy between the longer axis and the shorter axis of a light source, so that the light is diffused only when being rotated about the longer axis of the light source.

The lights from two or more directions are used for changing the incident angle of the light with respect to the surface of the sample to be cured for curing. If the difference of the angle of light coming from the adjacent

two light sources onto the sample is 50° or larger, the angular range of diffusion of the diffusion film become narrower. Therefore, the angle is preferably within 50°, and more preferably, within 30°.

Subsequently, a method of manufacturing a film having a curved waveguide array structure used in Claims 8 to 14 of the present invention will be described.

The film is obtained by manufacturing a waveguide structure which is not curved by irradiating light onto a mixture of at least two types of photo-polymerizable monomer or oligomer having different refractive indexes for curing the same, and physically bending the same.

The photo-polymerizable monomer or oligomer is monomer or oligomer having at least one polymerizable group such as acryloyl group, metaacryloyl group, vinyl group in a particle. A mixture of a plurality of chemical compounds is applied on the substrate or encapsulated in the cell to obtain a film and cured gradually while irradiating light.

The light to be irradiated may have any wavelength as long as it can cure the compound which includes monomer or oligomer, and, for example, visible light beam or ultraviolet beam is often used.

The ultraviolet beam is irradiated by using a mercury lamp or a metal halide lamp or the like. However, when a rod-shaped lamp is used, by adjusting the conditions of

irradiation, the obtained sheet like cured substance is caused to have anisotropy between the longer axis and the shorter axis of the light source, so that the light can be diffused only when being rotated about the longer axis of a light source.

The film generated in this manner has a structure in which the optical waveguide of the step index type and the optical waveguide of the type having a distribution of refractive indexes which brings out a light-collecting property in the direction of the layer thickness fused with each other.

By soaking the film in an organic solvent to soften and applying a physical force to curve the waveguide structure which has not been curved, the film having a curved waveguide array structure used Claims 8 to 16 of the present invention is obtained. The organic solvent may be of any type as long as it can soften the film without impairing the structure of the waveguide of the film.

First Embodiment

The diffusion film used in a first embodiment corresponds to the film (1), and as shown in Fig. 20, it is divided into the incident side portion and the outgoing side portion in structure. In the incident side portion is formed of layer array which corresponds to the optical waveguide of the step index type, in which the difference

between the refractive indexes n_1 and n_2 of the two types of layers laminated alternately in the y-direction is relatively small, and fluctuations in the layer inclination angle is large. On the other hand, the outgoing side portion is formed of layer array which corresponds to the optical waveguide of the step index type in which the difference between the refractive indexes n_1 and n_2 of the two types of layers laminated alternately in y-direction is relatively large, there are little fluctuations in the layer inclination angle, and the layer inclination angle is $-3°$ with respect to the normal line to the film. The diffusion film has values $y_{max} = 4\mu m$ and $L = 300$ μm, which satisfies the requirement in Claim 3, $(L \geq 10 \times y_{max})$.

The refractive indexes of the incident side portion are $n_1 = 1.5325$, $n_2 = 1.5275$, and the difference in refractive indexes $\Delta n = n_1 - n_2 = 0.005$. The distribution of the layer inclination angle includes two factors; first components being fluctuated substantially uniformly between $0°$ and $+6.5°$, and second components which exist at $0°$ intensively as an example of the measurements shown in Fig. 13 and summary shown in Fig. 20. A "frequency" of the layer inclination angle in Fig. 13 and Fig. 20 corresponds to the "existential probability" described above. The first components realize the diffusion characteristics of the top hat type, and the second components form a peak of the

measurements.

When the values of θ_1', θ_1'', θ_2' and θ_2'' are calculated by substituting the values for the parameters in the incident side portion, that is, $\theta + \Delta\theta_{max} = 6.5°$, $\theta - \Delta\theta_{max} = 0°$, $n_1 = 1.5325$, $n_2 = 1.5275$ in the expressions (1) to (4) which express the diffusion characteristics, $\theta_1' = 17.2°$, $\theta_1'' = 7.11°$, $\theta_2' = 2.87°$, and $\theta_2'' = -7.11°$ are obtained. Therefore, from the expression (5), the angular range of diffusion of the outgoing light θ_{out} of this incident side portion is; $-7.11° \leq \theta_{out} \leq 17.2°$. Therefore, the light incoming within the range of $-7.11° \leq \theta_{in} \leq 17.2°$ diffused substantially uniformly within the range of $-7.11° \leq \theta_{out} \leq 17.2°$ due to the first components.

Subsequently, this light enters into the layer array of the outgoing side portion. The refractive indexes of the outgoing side portion are $n_1 = 1.55$, $n_2 = 1.51$, the difference in refractive index is $\Delta n = n_1 - n_2 = 0.04$, and the layer inclination angle is $-3°$. Therefore, there are little fluctuations.

The light diffused substantially uniformly within the range of $-7.11° \leq \theta_{out} \leq 17.2°$ in the incident side portion is caught by the optical waveguide of the step index type having the value $n_1 = 1.55$, which constitutes the outgoing side portion, and repeats the multiple reflections. The light assumes a uniformly diffused light of $-4.58° \leq \theta_{in} \leq$

11.0° within the outgoing side portion, and the layer
inclination angle is -3°. Therefore, the lights within the
angular range of $-4.58° \leq \theta_{in} \leq -3°$ and $-3° \leq \theta_{in} \leq 11.0°$
repeat total reflections symmetrically about -3° as a center.
However, the angular range of the light that allows total
reflection in the angular range of $-3° \leq \theta_{in} \leq 11.0°$ is the
light within the range $-3° \leq \theta_{in} \leq 10.0°$ since $n_1 = 1.55$, $n_2 = 1.51$. Therefore, the light is diffused substantially
uniformly within the angular range of $-16.0° \leq \theta_{in} \leq 11.0°$
inside the outgoing side portion. When the light within
this range goes out into the air layer, the light diffuses
substantially uniformly within the angular range of $-25.4° \leq \theta_{out} \leq 17.2°$. This substantially coincides with the
measurements.

Subsequently, the peak of the light will be analyzed.
Since the peak of frequency exists at the point of 0° in the
distribution of the layer inclination angle in the incident
side portion, when the light enters at the angle of 0°, this
incident angle travels through the incident side portion at
the angle of 0° by the influence of the peak. When this
traveled light enters into the outgoing side portion, it is
totally reflected in the layer at -3°. Therefore, this
light travels in the direction of -6° when it is reflected
by an odd number of times and in the direction of 0° when it
is reflected by an even number of times. Consequently

lights of 0° and -6° are generated. When these lights go out into the air layer, they travel in the directions of 0° and -9.32°, and hence, the peaks are generated at 0° and - 9.32° in the measurements.

Second Embodiment

The diffusion film used in the second embodiment corresponds to the film (3) and, as shown in Fig. 21, is divided into the incident side portion and the outgoing side portion in structure. The incident side portion is formed of the layer array of the gradient index type, and the outgoing side portion is formed of the layer array of the step index type. Although this diffusion film is the same as that in the first embodiment by itself, in the second embodiment, the incident side portion of the diffusion film is also applicable to the model of the above-described gradient index type, and the fact that the diffusion characteristics can be described satisfactorily with this model is shown.

In the layer array in the incident side portion, the optical axes of the waveguides are fluctuated as shown in a measurement example in Fig. 13. The term "the optical axes are fluctuated" means that angles formed between the optical axes and the normal line of the film plane (corresponds to the angle of layer inclination in Fig. 13) are fluctuated. The refractive index distribution function of within each

waveguide is a parabolic distribution function shown by the expression (6), and the parameters are $b_1 = 2$ μm, $n_1 = 1.5325$, and $n_2 = 1.5275$. Therefore, $A = 6.525 \times 10^9$ is obtained from the expression (9), and $P/2 = 38.89$ μm is obtained from the expression (8). Since fluctuations of the optical axes are within the range between 0° and 6.5°, the expression (7) may be established when $\theta = 0°$, that is, $L_{zmax} = L_{zmin} \geq 38.89$ μm. In this embodiment, $L_{zmax} - L_{zmin}$ is on the order of 40 μm as shown in Fig. 21, the incident light can be diffused uniformly. Although the optical axes are fluctuated in the range between 0° and 6.5° in the diffusion film in this embodiment, the waveguides which determine the edge portion of having the diffusion characteristics of the top hat type are the waveguides at 0° and 6.5°, and hence the analysis will be made for 0° and 6.5°.

The wave guide at 6.5° will be analyzed first. In the waveguide, the light meandering within the range obtained by the expression (15). Therefore, the angle of diffusion by this waveguide is from -0.557° to 13.56°. When it is assumed that $n_1 = n_g$ is established, this diffuse light enters into the layer array of the step index type which constitutes the outgoing side portion. The parameters on the outgoing side are: $n_1 = 1.55$, $n_2 = 1.51$, and the difference of refractive index $\Delta n = n_1 - n_2 = 0.04$, and the layer inclination angle is -0.3°. Therefore, there are

little fluctuations.

The light which is uniformly diffused within the range between -0.557° and 13.56° in the incident side portion is caught by the optical waveguide of the step index type of n_1 = 1.55 on the outgoing side portion, and repeats the multiple reflections. Within the outgoing side portion, the light is converted into the uniform diffuse light in the range between -0.551° and 13.4°, and the layer inclination angle is -3°. Therefore, the light repeats the total reflections symmetrically about -3° as a center. However, the angular range of the light that allows total reflection in the angular range between -0.551° and 13.4° is only the angular range between -0.551° and 10° since n_1 = 1.55, and n_2 = 1.51. Therefore, the light is diffused within the angular ranges between -16.0° and -5.45°, and -0.551° and 13.4° uniformly inside the portion of the outgoing side. Although there is no light in the range between -5.45° and -0.551°, since the optical waveguides of the gradient index type of 0° to 6.5° fill therein, the light is diffused uniformly within the angular range between -16° and 13.4°. When this light is emitted to the air layer, the light is diffused within the angular range between -25.4° and 21.1° uniformly.

When the case in which the waveguide of the gradient index type in the incident side portion is 0° is analyzed in the same manner, the light emitted from the outgoing side

portion diffuses uniformly within the angular range between
-20.4° and 10.9°. Therefore, the light is diffused
uniformly in the angular range between -25.4° and 21.1° with
the lamination model including the incident side portion
composed of the layer array of the optical waveguides of the
gradient index type whose optical axes are fluctuated in the
range between 0° and 6.5° and the outgoing side portion
composed of the layer array of the optical waveguides of the
step index type which are included in the range between -
25.4° to and 21.1°.

Subsequently, the peak of the light will be analyzed.
Since the peak of frequency exists at the point of 0° in the
fluctuation distribution of the optical axes of the
waveguides in the incident side portion, if there is a gap
between the waveguides at 0°, part of light may go through.
When the incident angle is 0°, this light passes through as
is to the outgoing side portion. Since the layers on the
outgoing side portion are inclined by -3°, the light is
totally reflected on the layer of -3°, and if it is
reflected by the odd number of times, it travels to the
direction of -6°, and when it is reflected by the even
number of times, it travels to the direction of 0°, and
hence the light of 0° and the light of -6° are generated.
When these lights go out to the air layer, it travels to the
direction of 0° and -9.32°, and hence the peaks are

generated at 0° and -9.32° in the measurement.

Third Embodiment

In a third embodiment, as shown in Fig. 41 (a), a structure which is optically equivalent to the curved waveguide structure of the light-outgoing direction converting/diffusing film used in the present invention is obtained by arranging an optical film strip 9A obtained from an optical film 9 having a structure in which layers 9_1 and layers 9_2 are arranged in piles alternately in the direction of the planer having different refractive indexes in a bent manner as shown in Fig. 41(b). The thickness of each layer is 2 μm. The respective layer has a structure including the optical waveguide of the step index type in which the radius of curvature of the layer interface is locally varied and the optical waveguide of the gradient index type in which the length of the layer is varied fused with each other, and the refractive index at the center of the layer thickness is 1.55 in the layer 9_1 and is 1.51 in the layer 9_2. In order to prevent total reflection on the air interface, as shown in Fig. 41(b), the periphery of the bent optical film strip 9A is filled with transparent medium 12 having refractive index of 1.6. The radius of curvature is 4 cm for the minimum layer, which is sufficiently larger than either of the $R_{minstep}$ of the expression (1-16) and the R'_{min} of the expression (2-32).

An experiment to cause light (incident light 11_1) to be entered into the optical film strip 9A arranged in a curved state as described above from the side of one end surface using a light source 11 is conducted, and the fact that the light goes out from the side of the other end surface as an outgoing light 11_2 is confirmed. The intensity of the outgoing light 11_2 is substantially the same as the intensity of the incoming light 11_1.

Fourth Embodiment

In a fourth embodiment, a detailed example of a design in which the NA matching between the light-outgoing direction converting film and the optical engine is performed in the case in which the screen corresponding to Claim 8 (the light-outgoing direction converting film of the step index type + diffusing film) is applied to the actual thin-type rear projection display system shown in Fig. 33.

The optical system deployed with the mirrors M1, M3 and the non-spherical mirror M2 of the actual system removed is as shown in Fig. 27.

In the actual system, as shown in Fig. 33, the light changes the direction three times by the mirrors M1, M2 and the non-spherical mirror M2 on the backside of the screen 10, and the output light from the optical engine 20 is bent traversely by the mirror M1 which is located immediately in front toward the side. Assuming that the depth of the

actual system (a distance between the surfaces of the mirror M3 and the screen 10) is 20 cm, the height of the screen 10 is 1 m, and the distance between the centers of the lens and the mirror M1 is 40 cm, b = 20 cm × 3 + 40 cm = 1 m, S_2 = 1 m in the deployed optical system in Fig. 27. Assuming that the vertical length of an image display panel 21 (= S_1 in Fig. 27) including the DMD chip is 2.5 cm, a = 2.5 cm from the magnification S_2/S_1 = 1 m/2.5 cm = 40 = b/a = 1 m/a, and the focal distance f of the lens is f = 2.44 cm from 1/a + 1/b = 1/f. A lens diameter d is 2.4 cm. When l_1 = 30 cm, l_2 = l_1 + S_2 = 130 cm.

Since a parameter of the optical system is now determined, from the expressions (0-2) and (0-3), θ_1 and θ_0 in Fig. 27 is θ_1 = 52.474° and θ_0 = 16.066°. The range of the angle θ_{opt} which determines the output NA of the optical system is between θ_0 and θ_1 inclusive. When this range matches the range of the incoming angle of the light-outgoing direction converting film, the NA matching is achieved.

Since the range of the input angle of the light-outgoing direction converting film of the step index type is between θ_{in4} and θ_{in5} inclusive from the expression (1-12), the conditions of achievement of the NA matching is θ_{in4} = θ_0 = 16.066°, θ_{in5} = θ_1 = 52.474°.

Subsequently, θ_{bend} (corresponds to $\theta_{bend-in}$) will be

calculated. θ_{bend} is calculated by the following expression which is derived from an expression derived by substituting $+\theta_{in4}$ for $-\theta_{in4}$ in the expression (1-9), and the expression (1-11).

$\theta_{bend} = 1/2 \times [\sin^{-1}(n_{air}/n_g \times \sin\theta_{in4}) + \sin^{-1}(n_{air}/n_g \times \sin\theta_{in5})]$ .... (1-21)

When calculating by substituting the respective values described above for θ_{in4} and θ_{in5}, and assuming $n_g = 1.5$ and $n_{air} = 1.0$, $\theta_{bend} = 21.275°$ is obtained.

Subsequently, the radius of curvature of the bent waveguide is calculated. In this calculation, r_0 is calculated by entering the values of θ_{in5}, θ_{bend}, n_g, n_{air}, n_1, n_2, y_1 (width of the optical waveguide = layer thickness) in the following expression:

$\sin[\cos^{-1}\{n_g/n_1 \times \sin(\sin^{-1}(n_{air}/n_g \times \sin\theta_{in5}) - \theta_{bend})\}] = n_2/n_1 \times (1 + y_1/r_0)$ .... (1-11B)

which is obtained by modifying the expression (1-11), and, from $R = r_0 + y_1/2$, the radius of curvature is obtained. When the r_0 is obtained assuming that the θ_{in5}, θ_{bend}, n_g, n_{air} are the above-described respective values, and that $n_1 = 1.55$, $n_2 = 1.51$, $y_1 = 4$ μm, $r_0 = 401.617$ μm is obtained. Therefore, the radius of curvature is represented by $R = r_0 + y_1/2 = 403.617$ μm.

When θ_{bend} is used, since the thickness t_f of the film is $(r_0 + y_1) \times \sin\theta_{bend}$ from Fig. 42, and hence the expression t_f

$= (r_o + y_1) \times \sin\theta_{bend} = 147.2$ μm is established.

On the other hand, since the NA on the outgoing side is determined by the expression (1-5), when the r_0 and other parameters obtained above are substituted into the expression (1-5), $\theta_{out2} = 16.084°$ is obtained. Therefore, from the expression (1-6), the angular range that determines the NA on the output side becomes $-16.084° \leq \theta_{NAstep} \leq +16.084°$.

Fifth Embodiment

In a fifth embodiment, a detailed example of a design in which the NA matching between the light-outgoing direction converting film and the optical engine is performed in a case in which the screen corresponding to Claim 9 (gradient index type light-outgoing direction converting film + diffusing film) is applied to the thin-type rear projection display system which is the same as in the fourth embodiment will be described.

The range of the angle θ_{opt} which determines the output NA of the optical system is between $\theta_0 (= 16.066°)$ and $\theta_1 (= 52.474°)$ inclusive as in the case of the forth embodiment. When this range matches the input angular range of the light-outgoing direction converting film, the NA matching is achieved.

The input angular range of the light-outgoing direction converting film of the gradient index type is, from the

expression (2-16A), between θ_{in1} and θ_{in2} inclusive.
Therefore, the conditions of achievement of the NA matching
is $\theta_{in2} = \theta_0 = 16.066°$, $\theta_{in1} = \theta_1 = 52.474°$.

Subsequently, θ_{bend} (corresponds to $\theta_{bend-in}$) is calculated.
θ_{bend} is calculated by the following expression which is
obtained by modifying the expression (2-12A).

$\theta_{bend} = \sin^{-1}(n_{air}/n_g \times \sin\theta_{in1}) - \sin^{-1}(n_1/n_g \times$
$\sin\theta_{NA0})$ .... (2-12B)

Here, θ_{NA0} is calculated by the expression (2-5): $\theta_{NA0} =$
$\tan^{-1}(n_1 \times \sqrt{A} \times y_1/2)$, and the A in the expression (2-5) is
calculated by the expression (2-2): $A = (8/y_1^2) \times (n_1 - n_2)/n_1$.

When 4 µm is substituted for y_1, 1.55 is substituted for
n_1, and 1.51 is substituted for n_2 in the expression (2-2), A
$= 1.290 \times 10^{10}$ is established. When the value A and the
above-described y_1, n_1 values are substituted into the
expression (2-5), $\theta_{NA0} = 19.397°$ is established. Therefore,
the value of θ_{NA0}, the θ_{in1}, the value of n_1, $n_g = 1.5$, $n_{air} =$
1.0 are substituted into the expression (2-12B), so that θ_{bend}
$= 11.848°$ is determined.

Subsequently, the value n is determined. The value n
is calculated using the following expression obtained by
modifying the expression (2-15A).

$n = \theta_{NA0}/[\theta_{NA0} - \sin^{-1}\{n_g/n_1 \times \sin\{\theta_{bend} - \sin^{-1}(n_{air}/n_g \times$
$\sin\theta_{in2})\}\}]$ .... (2-15B)

The respective values corresponding to the parameters

in the expression is substituted into the expression (2-15B), so that n = 1.0646 is determined.

Then, the radius of curvature of the bent waveguide is calculated. In this calculation, the value A is substituted into the expression (2-4): $P = 2 \times \pi / \sqrt{A}$ to obtain P = 55.32 μm, and then the value P, the value of θ_{NA0}, and the value n are substituted into the expression (2-30): $R = r_0 + y_1/2 = (P/4)/\tan(\theta_{NA0}/(2 \times n))$, so that the radius of curvature R = 86.247 μm is determined.

From Fig. 42, since the thickness t_f of the film is $(r_0 + y_1) \times \sin\theta_{bend}$, when using θ_{bend}, $t_f = (r_0 + y_1) \times \sin\theta_{bend} = 18.1185$ μm (when $\theta_{bend-out} = 0°$).

On the other hand, the NA on the output side is designed by the output symmetry on the upper and lower sides. The angle of the optical axis on the output side θ_{axis} (= $\theta_{bend-out}$) is obtained by substituting the respective values corresponding to the parameters in the expression (2-26), which is θ_{axis} (= $\theta_{bend-out}$) = 9.4273°. Therefore, from the expression (2-27), $\theta'_{out3} = \theta'_{out4} = 16.084°$. Therefore, from the expression (2-28), the range of the angle which determines the output NA which is symmetry on the upper and lower side of the light-outgoing direction converting film is $-16.084° \leq \theta_{NAout} \leq 16.084°$.

Industrial Applicability

The present invention can be used for designing and manufacturing the rear (or front) projection display screen.